MASTER 00-63c1

NATIONAL WATER RESEARCH INSTITUTE

INSTITUT NATIONAL DE RECHERCHE SUR LES EAUX

HYDROGEOLOGICAL STUDIES IN SUPPORT OF THE RESTORATION OF THE WAINFLEET BOG: NUMERICAL MODELLING

A. Crowe, S. Shikaze and J. Smith

NWRI Contribution Number 00-63

Hydrogeological Studies in Support of the Restoration of the Wainfleet Bog: Numerical Modelling

Allan S. Crowe[1], Steve G. Shikaze[1], and James E. Smith[2]

[1]National Water Research Institute
Environment Canada
Canada Centre for Inland Waters
Burlington, Ontario, L7R 4A6

[2]School of Geography and Geology
McMaster University
Hamilton, Ontario, L8S 4M1

NWRI Contribution #00-063

Submitted to

The Niagara Peninsula Conservation Authority

March 2000

Abstract

The Wainfleet Bog, located in the Niagara Peninsula near Port Colborne, is currently undergoing a long-term restoration program to improve the degraded habitat and vegetative community within the Bog, and ultimately restore the bog to its original natural state. This report presents the results of computer simulations which assess factors relating to the resaturation of the Bog and its impact on the surrounding area. The spacing between drainage ditches within the Bog may have a major impact on the ability of the Bog to resaturate. When drainage ditches are relatively close together (e.g., 50 m), they will effectively prevent the water table within the peat from rising. No reasonable amount of increased infiltration or reduction in evapotranspiration will result in a rise in the elevation of the water table. Thus when ditches are closely spaced, they must be blocked. When drainage ditches are spaced far apart (e.g., 500 m or more), the ditches are only effective in draining peat adjacent to the ditch. Infiltration and evapotranspiration are the main controls on the elevation of the water table within the surrounding peat. The length of a blockage does not have a significant impact on the rise of the water levels in the drain or the adjacent water table upstream from the blockage. A blockage with a K_{sat} equal to that of peat (i.e., using peat as the material to construct a blockage) is just as effective in raising water levels as an impermeable blockage. Water will flow around the blockage regardless of its K_{sat} because the K_{sat} of the peat is high and conductive to groundwater flow. However, as the length of a blockage increases, the hydraulic gradient through and around the blockage will decrease dramatically, and hence the flow rate around and through the blockage will also decrease dramatically. Regional simulations showed that raising the water table within the bog by approximately 1 m will have not have a significant impact on the position of the water table within the surrounding area.

Background

The Wainfleet Bog, located in the Niagara Peninsula near Port Colborne (Fig. 1), is the largest remaining bog in Southern Ontario (Frohlich, 1997). Since the early 1800's human activities have decreased the size of the bog considerably from its original size. The expansion of agricultural lands into the bog and peat extraction from the bog itself occurred through the construction of numerous drainage canals around the periphery of the existing bog and within the bog itself. These drainage canals have caused extensive changes to the hydrology and hydrogeology of the Wainfleet Bog, and with it dramatic changes to its vegetative communities.

The Niagara Peninsula Conservation Authority, with support from the Ontario Ministry of Natural Resources, and the Nature Conservancy of Canada are currently undertaking a long-term restoration program to improve the degraded habitat and vegetative community within the Wainfleet Bog (Frohlich, 1997). The restoration program will be confined to the current boundaries of the Bog. An important component of the restoration program focuses on the hydrology and hydrogeology of the bog, and in particular the need to raise the water levels within the Bog. This report discusses the hydrogeological activities undertaken to date in support of the Niagara Peninsula Conservation Authority's plan to restore the Bog.

Objectives

The primary objective of the groundwater study is to determine if the water table within the Wainfleet Bog can be raised approximately one metre, and at the same time meet the following restrictions. First, the rise in the elevation of the water table within the Bog must not adversely affect the hydrology of the surrounding properties (e.g., adjacent fields should not be flooded). Secondly, the water table must rise slowly to enable wildlife (e.g., snakes, reptiles) whose habitat may be threatened by the rise or flooding sufficient time to relocate themselves. The groundwater studies required to address these objectives were undertaken through the following three tasks:

1. Investigate the hydrogeology of the Wainfleet Bog within a regional context.
2. Investigate the mechanics and hydraulics of peat resaturation.
3. Conduct computer simulations to assess various restoration scenarios.

This report focuses on the third objective, an analysis of the computer simulations undertaken to assess various restoration scenarios.

Field Activities

During June 14 to 25, 1999, six deep piezometers and seven shallow water table wells were installed using the NWRI drilling rig and drilling crew. The location of all monitoring wells is shown on Figure 1. In addition, one deep test hole was drilled to 100 feet (Fig. 1), but because coarse sediments were not encountered, it was decided that there would not be any hydrogeological value to completing this well. All wells were installed with 1" casing and screen, except WB #9, which was installed with 1.5" casing and screen. All casing and screen were screwed together. A sand and gravel pack was placed from the base of the screen to about 2' above the top of the screen. Two bags of benonite ("Well Seal") were inserted above the sand. The locations of the wells within the Bog were located with UTM coordinates using GPS. In addition, water level gauge bench marks were placed at four locations where the drainage canals flow from the Wainfleet Bog, as shown on Figure 1.

Students from the Environmental Science program at McMaster University have undertaken numerous field measurements of field-saturated hydraulic conductivity using a *Guelph Permeameter.* A total of 48 measurements were taken along four transects 50 m apart and perpendicular to the main road into the bog. The transects were selected to determine: (1) the field-saturated hydraulic conductivity of the peat, and (2) if the compaction of peat due to vehicle traffic had changed the hydraulic properties of the peat beneath the road. Tests were conducted both on the road and at 20 m and 40 m distances east from the road.

Hydrogeology

The field program undertaken for this study has revealed that two separate and distinct groundwater flow systems are present within the Wainfleet Bog area. A shallow or water table groundwater flow regime exists within the bog and the surrounding land. Here the depth to the water table is relatively shallow, varying in depth from 1 m within the bog to 4 m in the surrounding area. The water table is primarily affected by meteorological conditions (precipitation, infiltration, evapotranspiration), and the drainage ditches within both the bog and the surrounding farm land. Groundwater appears to be flowing from the central portion of the bog to the surround drainage ditches, and is probably affected by the major connected drainage canals within the bog and the spacing of these internal drains. The perimeter ditches around the bog appear to be effective in separating groundwater conditions within the bog with those in the farm land. Also, because of the low permeability of the clay, there is little flow of groundwater from the Bog into the surrounding area and vice versa.

A deep groundwater flow system has been identified within the gravel unit resting on bedrock. The hydraulic head within this unit is approximately 3-5 m lower that the elevation of the water table. The hydraulic heads of the deeper groundwater flow regime show considerably less range and variability than the water table. It is suspected that there is a strong connection between this basal gravel unit and the underlying fractured bedrock. Initial measurements indicate that this flow regime may be affected by the large quarry just to the south of the Wainfleet Bog. The two groundwater flow regimes, as well as the water in the Bog, are separated from each other by 60 to 80 m of clay. This clay forms an effective seal to separate the impact of the quarry dewatering on the Bog. Because of the head difference between the two flow systems, groundwater is slowly diffusing downward from the Wainfleet Bog.

There is no natural surface water flow system connected to the Bog. Thus, historically all water entering the Bog originated as precipitation and all water leaving the Bog did so as evapotranspiration. With the introduction of drainage ditches throughout the region and within the Bog, the source of water within the Bog remains as precipitation, but water is now removed from the Bog through the drainage ditches in addition to evapotranspiration.

Field measurements of the saturated hydraulic conductivity of the peat indicate that the field-saturated hydraulic conductivity of the peat tested is on the order of 10^{-5} m/s away from the road and about 10 times lower beneath the road.

MODELLING

A series of computer modelling analyses was undertaken to provide insight into the behaviour of the groundwater flow regime within the bog during resaturation. Specific objectives of the modelling analyses are:

1. evaluate the impact of internal and perimeter drains on controlling the water table and groundwater drainage/restoration within the bog.
2. evaluate various scenarios for drain closure which would be effective in raising the water table within the Bog.
3. provide insight into how raising water table within the Bog would impact on the surrounding farm land.

The modelling analyses to address these objectives were undertaken at three scales (Fig. 2):

1. an individual drain scale, to address objective 1.
2. a portion of the bog containing a drainage ditch, to address objective 2.
3. regional scale incorporating both the bog and the surrounding area, to address objective 3.

Objective 1: Drain Scale Simulations

Various scenarios were investigated at this scale to examine the effectiveness of the existing drains in controlling the water table within the Bog during drainage or resaturation, and specifically how far from a drain is the water table significantly lowered. These simulations were undertaken using a two-dimensional cross section (Fig. 3) to represent a section of the bog through and perpendicular to a drainage ditch. The boundary conditions consist of: (a) the upper boundary is a free surface (water table) boundary set initially 1 m below ground surface, with both the heads and elevation of the boundary allowed to rise and fall in response to hydrogeological changes, (b) the lower boundary is a no-flow boundary, representing the impermeable clay, set at 4 m below ground surface, and (c) the side boundaries are no-flow boundaries representing groundwater divides within the bog. In all cases the position of the water table was allowed to adjust in response to the drain and meteorological conditions. All simulations were undertaken using the GW-WETLAND model (Shikaze and Crowe, 1999). Parameters evaluated during the simulations include:

1. distance between drainage ditches

2. infiltration rate (precipitation - evapotranspiration)
3. seasonal fluctuations of the water level within the drainage ditch
4. zones of compacted peat (lower saturated hydraulic conductivity) within the bog
5. impact on the surrounding farm land

In all simulations, actual temperature and precipitation data measured at Port Colborne were used. Evapotranspiration data used represents that which occurs from Birch trees (M. Browning, pers. comm., see Appendix 1). Total annual precipitation and evapotranspiration used was 835 mm and 611 mm, distributed throughout the year. In all cases the water level within the drainage ditch falls 1 m from a spring high to its normal level within two weeks and remains at the lower level during the remainder of the year. Although the depth of the drainage ditches varies within the bog, the impact of the depth of drainage ditches was not simulated.

<u>Drainage Ditch Spacing of 50m</u>

The first set of simulations was run with a spacing of 50 m between the drainage ditches. This represents areas of the bog where the drains were closely spaced to assist in dewatering during the peat mining operations, such as that illustrated in Figure 3. Six simulations undertaken, with all simulations run to ten years (Table 1).

Table 1. Summary of 50 m ditch spacing simulations and water table changes.

Case	% precip. applied	% E.T. applied	water level drop in ditch	water table: spring[a] @ 25m	water table: fall[a] @ 25m
50m-1	0% P	0% ET	once	-1.00 m	-1.00 m[b]
50m-2	0% P	0% ET	annual	-0.86 m	-0.97 m
50m-3	100% P	100% ET	once	-0.48 m	-1.21 m
50m-4	75% P	100% ET	once	-0.65 m	-1.40 m
50m-5	50% P	0% ET	once	-0.63 m	-0.75 m
50m-6	75% P	0% ET	once	-0.45 m	-0.62 m
50m-7	100% P	0% ET	once	-0.33 m	-0.52 m

a: water table change at 25m between the drainage ditches during Mar. and Oct. of year 10 (-ve=fall, +ve=rise).
b: a drop of 1 m will place water table at the base of the peat and even with the water level in the drainage ditch.

The results of these 50 m ditch-spacing simulations, summarized in Table1 and the results are shown in Appendix 2. With no precipitation/infiltration (*case 50m-1*) the water table everywhere between the drainage ditches rapidly falls 1 m in less than a year. This coincides with the lower level within the drainage ditch. Even if the water level within the drainage ditch is allowed to cycle to a spring high each year (*case 50m-2*), the entire water table still falls 1 m to the level of water within the drainage ditch during each year.

Evapotranspiration and infiltration have a major impact on the water table. During the growing season, evapotranspiration lowers the water table but during the winter when evapotranspiration ceases, infiltration occurs resulting in a maximum water table elevation during the spring. This summer-fall decline and winter rise occurs each year giving rise to a seasonal cyclic pattern. Typical values of evapotranspiration and above-average infiltration (*case 50m-3*) cause the water table between the drains to rise and fall, but the maximum spring elevation of the water table is still 0.48 m below the initial water table. Also, evapotranspiration causes the water table to actually decline 0.21 m below the water level in the drainage ditch during the summer and fall. Decreasing the amount of infiltration (*case 50m-4*) results in even lower water levels during the summer and fall. To simulate the effects of artificially adding infiltration, or eliminating all evapotranspiration to raise the water table between the ditches, three simulations were run without considering the loss of groundwater via evapotranspiration. When the simulated net infiltration was 50% P-0% ET (*case 50m-5*), 75% P-0% ET (*case 50m-6*) and even as high as 100% P-0% ET (*case 50m-7*) of the actual precipitation, the drainage ditches were still able to effectively remove this additional water with the elevations of the water table (during the spring maximum) of 0.75 m, 0.62 m, and 0.52 m, below the initial water table, respectively.

These simulations show that a drainage ditch spacing of 50 m is very effective in lowering the water table throughout the peat between the drainage ditches. Thus, when the distance between drainage ditches is relatively small, the drainage ditch will prevent peat from resaturating unless the drains are blocked or filled. Eliminating all evapotranspiration or dramatically increasing infiltration will not result in a significant rise in the water table.

Drainage Ditch Spacing of 500m

The second set of simulations was run with a spacing of 500 m between the drainage ditches, representing areas of the bog where the drainage ditches were installed to remove water from an actively mined area to the perimeter drains (Fig. 4). Fourteen simulations were run (Table 2).

Table 2. Summary of simulations at a ditch spacing of 500 m and water table changes.

Case	% precip applied	% E.T. applied	compact zone[a]	K_{sat} compact zone[b]	ditch water change[c]	wat.table spring[d] 25m	wat.table fall[d] 25m	wat.table spring[d] 100m	wat.table fall[d] 100m	wat.table spring[d] 250m	wat.table fall[d] 250m
500m-1	0% P	0% ET	—	—	once	-0.83 m	-0.84 m	-0.46 m	-0.48 m	-0.19 m	-0.22 m
500m-2	0% P	0% ET	—	—	annually	-0.74 m	-0.81 m	-0.44 m	-0.46 m	-0.19 m	-0.21 m
500m-3	100% P	100% ET	—	—	once	+0.92m	+0.20 m	+2.80 m	+2.14 m	+3.90 m	+3.20 m
500m-4	85% P	100% ET	—	—	annually	+0.21 m	-0.56 m	+1.28 m	+0.60 m	+1.86 m	+1.23 m
500m-5	75% P	100% ET	—	—	annually	-0.38 m	-1.14 m	+0.08 m	+-0.66 m	+0.38 m	-0.34 m
500m-6	10% P	0% ET	—	—	once	-0.26 m	-0.26 m	+0.78 m	+0.81 m	+1.34 m	+1.39 m
500m-7	5% P	0% ET	—	—	once	-0.54 m	-0.54 m	+0.18 m	+0.19 m	+0.60 m	+0.62 m
500m-8	10% P	0% ET	—	—	annually	-0.19 m	-0.24 m	+0.79 m	+0.83 m	+1.34 m	+1.40 m
500m-9	5% P	0% ET	—	—	annually	-0.47 m	-0.51 m	+0.20 m	+0.21 m	+0.60 m	+0.62 m
500m-10	75% P	100% ET	10 m	$0.1K_{peat}$	annually	-0.11 m	-0.88 m	+0.20 m	-0.52 m	+0.45 m	-0.27 m
500m-11	75% P	100% ET	100 m	$0.1K_{peat}$	annually	-0.39 m	-1.17 m	+0.04 m	-0.68 m	+0.43 m	-0.29 m

a: distance to compacted zone of peat from the drain.
b: saturated hydraulic conductivity of the peat in a compacted zone relative to undisturbed peat.
c: spring water level change in the ditch: once - falls 1m only during spring year 1; annually – rises/falls 1 m each spring.
d: water table change between the ditches at 25m, 100m, 250m from each ditch in Mar. and Oct. of year 10 (-ve=fall, +ve=rise).

The change in the elevation of the water table obtained during these simulations is listed in Table 2, and the results are shown in Appendix 3. In the case where there is no precipitation/infiltration or evapotranspiration and only drainage to the ditch (*case 500m-1*), drainage of the entire area between the ditches is very slow. Although the water table will eventually decline to the elevation of that in the drainage ditches, it is very slow showing a decline of only 0.22 m in the centre after 10 years. Drainage close to the ditch is quite rapid, and the water table falls 0.84 m after 10 years. In the same situation but with an annual 1 m rise in the water level within the drainage ditches for 2 weeks each spring (*case 500m-2*), the results are essentially the same. Although there are fluctuations in the water table adjacent to the drainage ditch, after ten years the water table adjacent to the drainage ditch falls 0.81 m and towards the centre of the peat it falls 0.21 m.

When water is added and lost through infiltration and evapotranspiration, the water levels adjacent to the ditch and within the centre of the peat can change dramatically. With a high net infiltration rate (P-ET) of 100% precipitation and actual evapotranspiration (*case 500m-3*) groundwater adjacent to the ditch can drain but the water table will eventually rise 0.92 m after 10 years. In the centre of the peat, limited drainage to the ditches causes a continual rise in the water table, lowered only by evapotranspiration. Within a few years the water table will theoretically rise above ground surface, reaching a maximum elevation of 3.90 m above the initial water table after 10 years. With less infiltration, 85% precipitation (*case 500m-4*), the water table between the drainage ditches still rises above the original water table, but not as fast. The elevation of the water table within the centre of the peat is 1.88 m above the initial water table after 10 years. At 75% precipitation (*case 500m-5*), the water table between the drainage ditches slowly declines. Midway between the drainage ditches the water table fluctuates between 0.34 m below and 0.38 m above the initial water table due to infiltration and evapotranspiration. Thus, it would appear that a small net infiltration rate is required to raise the water table between the drainage ditches. A net infiltration of about 5% of precipitation will slowly raise the water table 0.62 m midway between drainage ditches whether the water level in the drainage ditch is at the base on the ditch for 10 years (*case 500m-7*) or rises and falls 1 m each spring (*case 500m-9*). A slightly higher net infiltration rate of 10% (*case 500m-6* and *case 500m-8*) will cause the water table to rise much higher, and in fact rise above ground surface. As in the previous examples, an annual rise in the water level within the drainage ditch vs. a single rise and fall in year one has a negligible effect on the long-term elevation of the water table away from the drainage ditch.

An additional set of simulations was undertaken with the drains 500m apart to investigate the effect of compacted peat near the drainage ditches. Field studies conducted as part of this hydrogeological investigation revealed that the peat beneath the roads and former railways within the bog have been compacted resulting in a saturated hydraulic conductivity of approximately one to two orders of magnitude lower than the surrounding uncompacted peat. In the following simulations a 5 m wide zone of compacted peat with a saturated hydraulic conductivity 10 times less that the surrounding peat was located 10 m or 100 m from the drainage ditches. The following simulations were run with 75% precipitation and 100% evapotranspiration because this net infiltration value produces water table fluctuations within the peat which are observed to occur in the bog (i.e., rise each spring, decline through summer-winter-fall) A 5 m wide zone of compacted peat with a one order of magnitude lower saturated hydraulic conductivity will essentially act as a barrier to drainage towards the ditch whether the compacted zone is 10 m (*case 500m-10*) or 100 m (*case 500m-11*) from the drainage ditch. Although the groundwater between the drain and the compacted zone is essentially drained, the water table within the centre of the peat (past the compacted zone) is essentially unaffected by the drains, falling only 0.27 m each fall vs. 0.34 m without a compacted zone (*case 500m-5*). The difference is more dramatic near the drainage ditch. When the compacted zone is 10 m from the ditch, the water table decline in the spring after 10 years is 0.88 m (*case 500m-10*) vs. 1.14 m without the compacted zone (*case 500m-5*).

Thus, when drainage ditches are quite far apart, the ditches are relatively ineffective in controlling water levels within the majority of the peat between drainage ditches. The drainage ditches effectively drain only an area of the peat adjacent to the drainage ditch. The water required to saturate the peat must come from increased net infiltration (i.e., reduced evapotranspiration), and not from reducing or eliminating flow from the peat into the drainage ditch. These simulations show that only a small net increase in infiltration in the order of 5% is required to raise the water table. Also, if a compacted zone exists near the drainage ditch, this zone will act as a barrier to saturating peat with water from the drainage ditches. However, the impact of the water levels within the drainage ditches on peat resaturation is essentially localized to the areas near the drainage ditch, and the water required to raise the water table over large areas of the bog must come from net infiltration. Thus, the compacted zones will have a minimal impact on peat resaturation throughout a large area of the bog. Also, short-term seasonal fluctuations in the water levels in the drainage ditches have a minimal impact on the water table within the peat more than 100 m from the ditch.

<u>Drainage Ditch Spacing of 2000m</u>

The third set of drainage ditch simulations was run with a spacing of 2000 m between the drainage ditches to represent the impact of the perimeter drains on raising the water table within the bog (Fig. 5). Specifically, these simulations (Table 8) are designed to first, investigate the impact that the rising water table within the bog would have on the water table in the adjacent farm land outside the bog, and second, investigate changes to the water table within the Bog if all internal drainage ditches where blocked or filled.

The resulting changes to the elevation of the water tables obtained during these simulations is summarized in Table 3, and the results are shown in Appendix 4. The first group of simulations undertaken with drainage ditches separated by 2000 m, verify much of the previous results from the drainage ditches at a 500 m spacing: drainage ditches far apart are relatively ineffective in draining the peat. With only drainage to the ditches via groundwater flow and no precipitation/infiltration or evapotranspiration (*case 2000m-1*), only the area adjacent to the drain experiences a decline in the elevation of the water table. After 10 years the water table at the centre of the peat has not changed, but the drain has impacted the saturated zone to approximately 200 m from the drain, including a decline of 0.46 m at 250 m from the drainage ditch An annual 1 m rise and fall in the water level within the ditch each spring (*case 2000m-2*), shows essentially the same results as when the water level in the drainage ditch falls 1 m at the start of the simulation and remains there for 10 years (previous case).

Table 3. Summary of simulations at a ditch spacing of 2000 m and water table changes.

Case	% precip applied	% E.T. applied	clay zone[a]	ditch water change[b]	wat.table spring[c] 100m	wat.table fall[c] 100m	wat.table spring[c] 250m	wat.table fall[c] 250m	wat.table spring[c] 1000m	wat.table fall[c] 1000m
2000m-1	0% P	0% ET	—	once	-0.45 m	-0.46 m	-0.10 m	-0.11 m	0.00 m	0.00 m
2000m-2	0% P	0% ET	—	annually	-0.43 m	-0.44 m	-0.09 m	-0.10 m	0.00 m	0.00 m
2000m-3	100% P	100% ET	—	once	+3.00 m	+2.38 m	+4.50 m	+3.99 m	+5.15 m	+4.73 m
2000m-4	70% P	100% ET	—	once	-0.65 m	-0.38 m	-0.39 m	-1.13 m	-0.32m	-1.03 m
2000m-5	75% P	100% ET	—	once	+0.08 m	-0.65 m	+0.50 m	-0.21 m	+0.63 m	-0.07 m
2000m-6	65% P	100% ET	—	once	-1.43 m	-2.24 m	-1.26 m	-2.11 m	-1.25 m	-2.06 m
2000m-7	65% P	100% ET	—	annually	-1.39 m	-2.20 m	-1.28 m	-2.10 m	-1.24 m	-2.06 m
2000m-8	75% P	100% ET	—	annually	-0.63 m	-1.40 m	-0.39 m	-1.15 m	-0.31 m	-1.07 m
2000m-9	10% P	0% ET	—	once	+0.83 m	+0.88 m	+1.59 m	+1.69 m	+1.83 m	+1.98 m
2000m-10	5% P	0% ET	—	once	+0.21 m	+0.23 m	+0.79 m	+0.81 m	+0.92 m	+1.00 m
2000m-11	1% P	0% ET	—	once	-0.31 m	-0.32 m	+0.08 m	+0.08 m	+0.18 m	+0.20 m
2000m-12	0% P	0% ET	yes	once	-0.45 m	-0.47 m	-0.10 m	-0.11 m	0.00 m	0.00 m
2000m-13	5% P	0% ET	yes	once	+0.21 m	+0.23 m	+0.76 m	+0.81 m	+0.92 m	+1.00 m
2000m-14	75% P	100% ET	yes	once	+0.07 m	-0.67 m	+0.50 m	-0.22 m	+0.63 m	-0.08 m
2000m-15	100% P	100% ET	yes	once	+2.99 m	+2.30 m	+4.49 m	+3.93 m	+5.15 m	+4.70 m

a: clay zone adjacent to drain at edge of the peat, representing the boundary of the bog.
b: spring water level change in the ditch: once - falls 1m only during spring year 1; annually - falls 1 m each spring.
c: water table change between the ditches at 100m, 250m, 1000m from each ditch in Mar. and Oct. of year 10 (-ve=fall, +ve=rise).

Adding and removing water through infiltration/precipitation and evapotranspiration, respectively are the primary factors affecting the rise or fall of the water table between the drainage ditches. If a net infiltration rate of 100% precipitation – actual (100%) evapotranspiration occurred (*case 2000m-3*), the drains could not remove the excess infiltration entering the peat away from the ditch. Hence, the water table would theoretically rise 5.15 m (above ground surface) midway between the ditches and 4.50 m at a distance of 250 m from the ditches in the spring after 10 years.

A more realistic amount of infiltration of 70% precipitation - 100% evapotranspiration (*case 2000m-4*) results in fluctuating water levels which continually decline to where, after 10 years, the spring and fall decline from the original water table is 0.32 m and 1.03 m, respectively. A slightly higher infiltration rate of 75% precipitation - 100% evapotranspiration (*case 2000m-5*) results in a very small net decline in the water table only adjacent to the drainage ditch. At 250 m and 1000 m from the drainage ditch, the water table fluctuates between being above the original water table (spring) and below the original water table (fall) due to dominant periods of infiltration and evapotranspiration. The change in the elevation of the water table is quite sensitive to the net infiltration rate, where a 5% decrease in precipitation from 70% to 65% (*case 2000m-6*) results in a dramatic decline in the elevation of the water table of 2.06 m after ten years. Simulating these cases but with a 1 m annual rise and fall of the water level in the drainage ditch each spring, results in a negligible change in the elevation of the water table. With a net infiltration rates of 65% precipitation - 100% evapotranspiration (*case 2000m-7*) and a net infiltration rates of 75% precipitation - 100% evapotranspiration (*case 2000m-8*), the elevation of the water table fell 2.06 m and 1.07 m, respectively, in the centre of the peat.

To further estimate the amount of infiltration required to raise the water table at this scale, simulations where run with precipitation but no evapotranspiration. An infiltration of 10% precipitation - 0% evapotranspiration (*case 2000m-9*) results in a rapid and continuous rise in the elevation of the water table and in fact the water table rises 1.98 m and 1.69 m above ground surface midway between and 250 m from the drainage ditches in the fall after 10 years, respectively. An infiltration rate of 5% precipitation - 0% evapotranspiration (*case 2000m-10*) causes the water table to continually rise, and eventually reach ground surface (1.00 m above initial water table) midway between the drainage ditches after 10 years. Even a small infiltration amount of 1% precipitation - 0% evapotranspiration (*case 2000m-11*) results in a very slow and continuous rise in the elevation of the water table to 0.20 m above the initial water table midway between the drainage ditch because this infiltration can not drain to the ditches. Adjacent to the drainage ditches (within 100 m), the water table is affected by drainage to the ditch. 100m from the ditch, the water table rise for 10% and 5% P (0% ET) is much less than the rise further away from the ditch. For an infiltration rate of 1% P and 0% ET, the water table 100 m from the drainage ditch actually falls 0.31 m.

The next group of simulations was designed to investigate the impact that raising the water table within the bog would have on the adjacent farm land. Field studies have shown that the dominant geological material in the adjacent farm land is clay, and hence the simulations were undertaken with a zone of clay adjacent to the drainage ditches and outside of the bog. In order to assess the impact of changing water levels within the bog on the adjacent farm land, all the following simulations were undertaken assuming no infiltration into the clay in order to asses only the impact of a rise in the water table within the bog on water levels in the clay. In the simulation with no infiltration or evapotranspiration (*case 2000m-12*), the water table 100 m from the drainage ditch into the peat falls 0.47 m in ten years (same results as *case 2000m-1*), whereas at the same distance from the drainage ditch in the clay, the water table did not decline. When a small amount of infiltration (5% precipitation - 0% evapotranspiration) was added within the bog (*case 2000m-13*), the water table 100 m from the drainage ditch into the peat rose 0.23 m after ten years (same results as *case 2000m-10*), whereas at the same distance from the drainage ditch in the clay, the water table did not change. When high rates of infiltration and evapotranspiration are used (*case 2000m-14* and case *2000m-15*), the water table in the peat fluctuates considerably and rises above the initial water table (same results as *cases 2000m-5* and *2000m-3*) but again there is no change in the clay 100 m from the drainage ditch. Thus, the very low hydraulic conductivity of the clay should prevent an adverse rise in the water table in the adjacent farm land when the water table within the bog rises.

Objective 2: Drain Closure Simulations

Simulations undertaken at this scale are designed to provide insight into where the blockages in the drainage ditches should be placed, and how effective various blockages would be in retaining water within the adjacent peat. In addition to predicting water level changes in response to drain blockages, the simulations also estimate rates of flow around the blockage.

A three dimensional block of peat which included one or more drainage ditches was simulated. The numerical code used for these simulations is FRAC3DVS (Therrien et al., 1999). The simulations were performed using a rectangular 3-D block of peat 500 m in the direction of the drainage ditch by 1005 m perpendicular to the drainage ditch by 5 m thick (Fig. 6). The block is designed to simulate a uniform 4 m thick layer of peat overlying a 1 m layer of clay, with an initial water table depth of 1 m below the ground surface for all simulations. For boundary conditions, the up-gradient and down-gradient faces of the 3-D block were specified as constant head nodes in order to establish a hydraulic gradient, and hence groundwater flow, across the peat-block parallel to the drainage ditch. The gradient in all simulations is a 0.5 m drop in head along the 500 m length of the block. Across the top face of the block, a small amount of recharge has been added, and all other boundaries have been set as no-flow. Two depths of drainage ditches were simulated, a 4 m deep drainage ditch which is 3 m below the water table and to the peat-clay interface, and a 2 m deep drainage ditch which is 1 m below the water table and its base is within the peat.

Parameters evaluated in these scenarios include:

1. direction of groundwater flow within the peat
2. depth of a drainage ditch
3. material at the base of the drainage ditch (clay or peat)
4. length of the blockage
5. number of blockages per drain
6. saturated hydraulic conductivity of the blockage material.

These simulations are listed in Table 4, and the resultant changes in water levels due to the drainage ditch blockages shown in Appendix 5. Water level changes due to the blockages in the drainage ditches are reported for two locations. The first head change (Table 4, column 6) represents a difference in the water level in the drainage ditch 20 m upstream from the blockage, or in cases of two blockages (*cases block-16* and *block-18*), 20 m upstream from the upstream blockage. The second head change (Table 4, column 7) represents a water table change 20 m upstream of the blockage and 50 m perpendicular into the peat. Both head changes are measured relative to the corresponding base case (*case block-1* to *block-4*).

Table 4. Summary of simulations with the 3-D block of peat and water table changes.

case	boundary condition[a]	drain depth[b]	blockage location	$K_{Blockage}$[c]	Δhead in ditch[d]	Δhead in peat[e]	flow around block to 5m[f]	flux around block to 5m[g]
block-1	full	1 m	none	—	—	—	—	—
block-2	full	3 m	none	—	—	—	—	—
block-3	full	1 m	5m @ 100-105m	$K_B = K_{peat}$	+0.20 m	+0.09 m	1.97 m^3/d	0.0492 m/d
block-4	full	1 m	5m @ 100-105m	$K_B = 0.1{*}K_{peat}$	+0.21 m	+0.09 m	1.99 m^3/d	0.0496 m/d
block-5	full	1 m	5m @ 100-105m	$K_B = 10{*}K_{peat}$	+0.14 m	+0.06 m	1.83 m^3/d	0.0456 m/d
block-6	full	3 m	5m @ 100-105m	$K_B = K_{peat}$	+0.28 m	+0.12 m	1.50 m^3/d	0.0500 m/d
block-7	full	3 m	5m @ 100-105m	$K_B = 0.1{*}K_{peat}$	+0.29 m	+0.13 m	1.51 m^3/d	0.0504 m/d
block-8	full	3 m	5m @ 100-105m	$K_B = 10{*}K_{peat}$	+0.17 m	+0.08 m	1.38 m^3/d	0.0461 m/d
block-9	full	3 m	100m @ 100-200m	$K_B = K_{peat}$	+0.27 m	+0.17 m	0.26 m^3/d	0.0085 m/d
block-10	full	3 m	100m @ 100-200m	$K_B = 0.1{*}K_{peat}$	+0.27 m	+0.17 m	0.30 m^3/d	0.0099 m/d
block-11	full	3 m	100m @ 100-200m	$K_B = 10{*}K_{peat}$	+0.27 m	+0.17 m	0.16 m^3/d	0.0053 m/d
block-12	full	3 m	5m @ 195-200m	$K_B = K_{peat}$	+0.27 m	+0.17 m	1.49 m^3/d	0.0497 m/d
block-13	full	1 m	100m @ 100-200m	$K_B = K_{peat}$	+0.27 m	+0.17 m	0.36 m^3/d	0.0090 m/d
block-14	full	3 m	2 x 5m @ 100m,200m	$K_B = K_{peat}$	+0.25 m	+0.14 m	0.87 m^3/d	0.0289 m/d
block-15	full	1 m	2 x 5m @ 100m,200m	$K_B = K_{peat}$	+0.48 m	+0.38 m	1.18 m^3/d	0.0292 m/d

a: full - groundwater flow into and out of entire face; ditch only - flow only through ditch.
b: depth below the water table.
c: saturated hydraulic conductivity of the peat in a compacted zone relative to undisturbed peat.
d: Δhead w.r.t. base case measured 20m upstream of blockage within ditch (125m from downstream boundary).
e: Δhead w.r.t. base case measured 20m upstream of blockage (125m from downstream boundary) and 50m into peat.
f: rate of groundwater flow (m^3/d) through the peat within 5 m of the blockage.
g: groundwater flux ($m^3/d/m^2$) through the peat within 5 m of the blockage.

Two initial simulations were run without blockages within the drainage ditch to provide a base groundwater flow regime from which the effectiveness of the blockages can be assessed. The first case has a drainage ditch which is 2 m deep (1 m below the water table), with groundwater flow within the peat parallel to the drainage ditch (*case block-1*). The next case has a 4 m deep drainage ditch (3 m below the water table) and again with groundwater flow within the peat parallel to the drainage ditch (*case block-2*). As expected these two cases show a continuous decrease in elevation of the water level along the ditch and groundwater flow from the peat into the ditch along its entire length.

The next set of simulations was run with a 5 m long blockage inserted into the drainage ditch. If the material comprising the blockage has the same K_{sat} as the peat (*case block-3*), upstream water levels in the drainage ditch will rise, as will the water table in the adjacent peat. Although the rise in the water level in the ditch 20 m upstream from the blockage is 0.20 m, the water table rise is only 0.09 m. However, because the peat is relative permeable and a large gradient through the peat around the blockage is formed, a considerable amount of water will flow from the drainage ditch around the blockage through the peat (1.97 m^3/d). Decreasing the K_{sat} of the blockage by an order of magnitude (*case block-4*) will raise the water levels in the drain and the surrounding peat by a negligible amount. Slightly more water will flow around the blockage through the peat (1.99 m^3/d), because it has a higher hydraulic conductivity than the blockage, hence less flow through the blockage. Increasing the K_{sat} of the blockage by an order of magnitude (*case block-5*) will cause more flow through the blockage and less around the blockage (1.50 m^3/d). Hence, the water level rise in the drainage ditch (0.14 m) and the adjacent peat (0.06 m) is lower. The results obtained for a 5 m long blockage in a 3 m deep drainage ditch are similar to those obtained for the 1 m deep drainage ditch. When K_{sat} of the blockage is the same as the peat (*case block-6*) or one order of magnitude lower (*case block-7*), the water level in the drainage ditch is higher and the water table in the adjacent peat is higher (~0.29 m and 0.12 m, respectively). There is also considerable flow around the blockage through the peat (1.50 m^3/d). The total flow around the blockage to a distance of 5 m into the peat is less than that for the 1 m deep drainage ditch (*cases block-3* to *block-5*). However, the flux (flow per unit area) is essentially the same because flow around the blockage in the 3 m deep drainage ditch extends further into the peat. When the K_{sat} of the blockage is an order of magnitude higher than the peat (*case block-8*), the rise in the water level in the drainage ditch and the water table in the surrounding peat is much lower because a large blockage with a high K_{sat} allows considerably more flow through the blockage than around the blockage (1.38 m^3/d).

Increasing the length of the blockage from 5 m to 100 m, and with a K_{sat} equal to that of peat (*case block-9*) or 10 times the K_{sat} of peat (*case block-10*), in a 3m deep drainage ditch does not significantly increase the water level within the drainage ditch (~0.27 m vs. ~0.28 m) or the surrounding water table (~0.17 m vs. ~0.12 m), but it does reduce the amount of flow through the peat around the blockage considerably. Both the total flow and flux within 5 m of the drainage ditch are considerably lower because of a lower gradient through the peat. Slightly more flow occurs when the K_{sat} of the blockage is 10 times the K_{sat} of the peat because there is more flow through the blockage when its K_{sat} is high (*case block-11*). The water table rise in the peat is slightly greater than *case block 6* and *case block-7* because the blockage has been moved closer to the upstream boundary of the flow domain. For example, *case block-12* shows that a 5 m blockage at the same upstream location as the 100 m, results in a head change the same as the 100 m blockage (*case block-10*), and the same flow/flux as the 5 m blockage (*case block-6*). A similar situation occurs in the 1 m deep drainage ditch with a 100 m long blockage and a K_{sat} equal to that the peat (*case block-13*); the water level rise in the ditch and the adjacent peat are the same as the previous cases, and both the flow rate around the blockage is higher than that for the 3 m deep ditch.

The final two simulations investigate the impact of replacing a single 100 m long blockage with two 5 m long blockages which are 95 m apart (i.e., the 5 m blockages correspond to the same locations as the upstream and downstream ends of the 100 m long blockage). The simulation using a ditch depth of 3 m (*case block-14*), shows a rise in the water levels in the drainage ditch (0.25 m) and the adjacent peat (0.14 m) which is slightly lower than that resulting from a single 100 m long blockage (*case block-9*). However, flow leaving the system around the downstream blockage is much higher (0.87 m^3/d vs. 0.26 m^3/d) because of higher gradients around each of the 5 m long blockages. The simulation using a 1 m deep ditch (case block-16) shows essentially the same results; slightly lower rise in the water levels in the drainage ditch (0.26 m) and the peat (0.14 m), but considerably higher flow around the downstream blockage (1.18. m^3/d vs. 0.36 m^3/d from *case block-13*).

Figure 7 illustrates the impact of blockage length on reducing flow or leakage of water through the adjacent peat around the blockage. This analysis was undertaken was a 2 m deep drainage ditch (1 m below the water table) in a block of peat with a K_{sat} of the blockage equal to K_{sat} of the surrounding peat. Figure 7a shows the total flow of water around the blockage along a cross section of peat through the downstream face of the blockage, with total volume (m^3/d) of groundwater flow to increasing distances from the drainage ditch. As expected for a specific length of a blockage, the amount of leakage increases with increasing distance from the drainage ditch because the total area of flow through which leakage occurs increases. However, the total flow to any distance (i.e., over equal areas) is considerable less for a long blockage than for a small blockage because the corresponding hydraulic gradient is considerably less. Figure 7b depicts the volume of flow (m^3/d) through a unit area of peat at various distances into the peat along a cross section through the downstream face of the blockage. This figures shows leakage through the peat around the blockage is concentrated close the blockage, and decreases rapidly into the peat from the blockage. Also, the amount of water flowing around the blockage through a unit area peat decreases exponentially away from the blockage. For both the 5 m and 100 m long blockages, almost all the flow due to leakage around the block is within approximately 25 m of the blockage, and beyond 25 m the flow is essentially all background groundwater flow.

Objective 3: Regional Scale Simulations

The three-dimensional regional-scale modelling was carried out using the same program as in the previous section (FRAC3DVS (Therrien et al., 1999)). The purpose of modelling at this scale is to examine the effect that higher water levels in the Bog will have on the surrounding are. The irregular domain was set up to be approximately 12 km in the east-west direction and 14 km in the north-south direction (Fig. 8). Stratigraphy was included and three geologic units have been added in the model: (1) the surficial clay, (2) bedrock, and (3) peat (Fig. 9). The thin gravel layer that is known to exist between the clay and the bedrock in some areas was not included, and we have assumed that the water levels in the bog will have no influence on this gravel unit. Depths to bedrock were estimated from the NWRI drilling program as well as existing borehole data.

The northern boundary was set as constant head to represent the Welland River. The eastern and southern boundaries were also set as constant head boundaries to represent the Welland Canal and Lake Erie, respectively. For all three of these boundary conditions, only the top layer of nodes was specified as constant head nodes. The western boundary of the domain was set as no-flow, as was the base of the 3-D domain. Recharge was added to the top of the domain where the bog exists.

Major drainage ditches were also specified as internal constant head nodes along the top boundary of the domain. Along the north and west of the Bog, the values of constant head nodes, which represent drainage ditches, were set up such that flow in these ditches is northward towards the Welland River. The drainage ditch along the south of the Bog has constant head values which are set up such that water in the ditch flows east towards the Welland Canal.

In order to establish initial conditions for a 10-year simulation (with increasing water levels in the Bog), a steady-state simulation was run with boundary conditions and recharge described above. Figure 10 shows a plan view of the hydraulic heads along the top of the 3D domain from this steady-state simulation. Because recharge is added to the Bog only, there is a groundwater mound that appears in the west end of the Bog. This result is consistent with observations from the field that show higher groundwater levels in the Bog relative to the surrounding area, and as a result, this simulation was presumed to be acceptable as an initial condition for the 10-year simulation.

The transient simulation was run to a time of ten years and the hydraulic heads along the top of the 3D domain are shown in Figure 11. For this simulation, rising water levels within the Bog are simulated by increasing the value of recharge that is applied to the Bog. Water levels throughout the domain are examined by including five monitoring wells, as shown in Figure 8. Wells 1 and 2 are located within the Bog, while Wells 3, 4 and 5 are located to the north of the Bog. For Wells 1 and 2, the water level rises approximately one metre over the 10-year simulation (Fig. 12), while at Well 3, the water level rises approximate 30 cm over 10 years. The water levels in Wells 4 and 5 do not appear to be significantly affected by the rise in the water table within the Bog.

The rate and magnitude of the rise in the water level is dependent upon the recharge rate, as well as physical properties of the peat, such as hydraulic conductivity and specific storage coefficient. As a result, any uncertainty associated with these values will result in uncertainty in the results from the model. Also, it should be noted that although hydraulic heads appear to be decreasing away from Lake Erie (southern boundary), the hydraulic head value chosen for the Lake Erie boundary condition represents a value that lies between the actual seasonal high and low. This is not expected to result in significant error in the water levels within the Bog because of the thick clay unit that exists below the peat material. However, modelled water levels shown in Figures 10 and 11 around the Bog may have more uncertainty associated with them as a result of the approximation made at the Lake Erie boundary. Moreover, water levels in the Welland River, the Welland Canal, and the drainage ditches were estimated, and assumed to be constant over the 10-year simulation. This too, could lead to some uncertainty in the results.

Consequently, results provided here should not be considered to represent the exact field conditions and should only be used as a guideline for what could happen in the field.

CONCLUSIONS

Impact of drainage ditches on controlling water levels within the bog

1. When drainage ditches are relatively close together (e.g., 50 m), they will effectively prevent the water table within the peat from rising. No reasonable amount of increased infiltration or reduction in evapotranspiration will result in a rise in the

elevation of the water table. Thus when ditches are closely spaced, they must be blocked.

2. When drainage ditches are spaced far apart (e.g., 500 m or more), the ditches are only effective in draining peat adjacent to the ditch. Infiltration and evapotranspiration are the main controls on the elevation of the water table within the surrounding peat.
3. When drainage ditches are spaced far a part, the water table is quite sensitive to small changes in the net infiltration rate. A small increase in infiltration (a few percent above current rates) will raise the water table.
4. The material beneath the perimeter drains and farm land to the north of the bog is clay, and given its low hydraulic conductivity, raising the water table within bog will result in a negligible change in water levels within this farm land.
5. Short-term seasonal fluctuations in the water level within the drainage ditch do not have a significant impact on the water table within the peat more than approximately 100 m from the drainage ditch.

Impact of various ditch blockages in controlling water levels and leakage

1. The length of a blockage does not have a significant impact on the rise of the water levels in the drain or the adjacent water table upstream from the blockage.
2. A blockage with a K_{sat} equal to that of peat (i.e. using peat as the material to construct a blockage) is just as effective in raising water levels as an impermeable blockage.
3. Water will flow around the blockage regardless of its K_{sat} because the K_{sat} of the peat is high and conductive to groundwater flow.
4. As the length of a blockage increases, the hydraulic gradient through and around the blockage will decrease dramatically, and hence the flow rate around and through the blockage will also decrease dramatically.
5. Two short (e.g., 5 m) blockages are no more effective than a single short blockage or a single long blockage (e.g., 100 m) in raising water levels in the ditch and the adjacent peat, but are less effective than a long blockage in reducing flow around the blockage.

Impact of raising the water table within the bog on the surrounding region

1. Raising the water table within the bog by approximately 1 m will have not have a significant impact on the position of the water table within the surrounding area.
2. Although the simulations showed that the 1 m rise in the elevation of the water table within the Bog took 10 years, the actual timing of the rise is highly variable, dependant upon drainage closures, heterogeneities within the peat, infiltration rates, and most importantly, the impact of evapotranspiration.

REFERENCES

Frohlich, K. 1997. Wainfleet Bog Management Plan, Wainfleet, Ontario. Niagara Peninsula Conservation Authority in association with the Wainfleet Bog Advisory Committee. 89 pp.

Shikaze, S.G. and A.S. Crowe. 1999. User's Guide for GW-WETLAND: A Computer Program to Simulate Groundwater Flow, Particle Tracking, and Solute Transport in a Two-dimensional Cross Section with Transient Boundary Conditions and a Fluctuating Water Table. National Water Research Institute Contribution 99-204, 65 pp.

Therrien, R., E.A. Sudicky and R.G. McLaren. 1999. User's Guide for NP 3.40. A Preprocessor for FRAC3DVS 3.40: An efficient simulator for three-dimensional, saturated-unsaturated groundwater flow and chain-decay solute transport in porous or discretely-fractured porous formations. Groundwater Simulations Group, Department of Earth Sciences, University of Waterloo, Waterloo, Ontario.

Figures

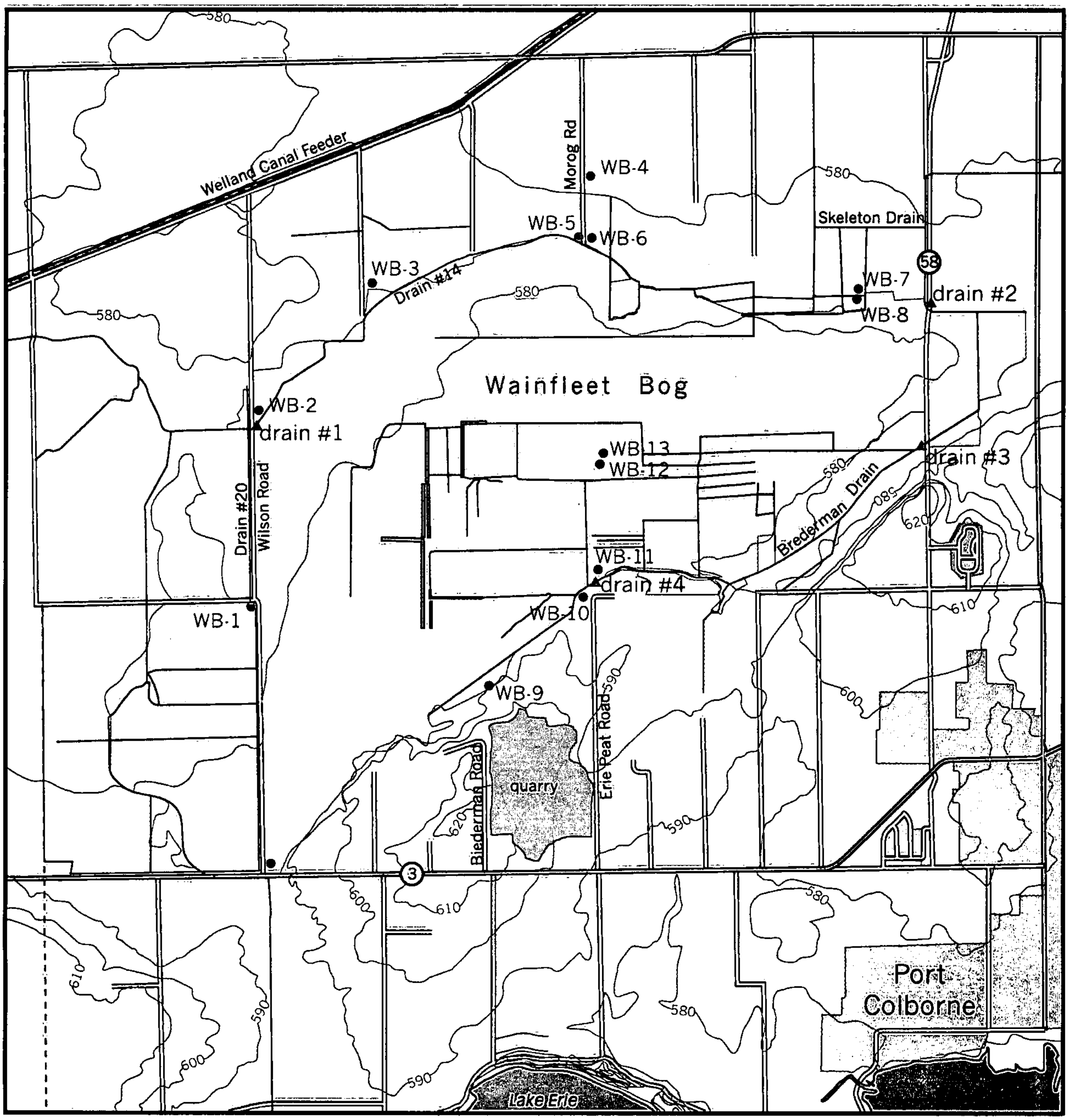


Figure 1 - Site map for the Wainfleet Bog, including location of wells.

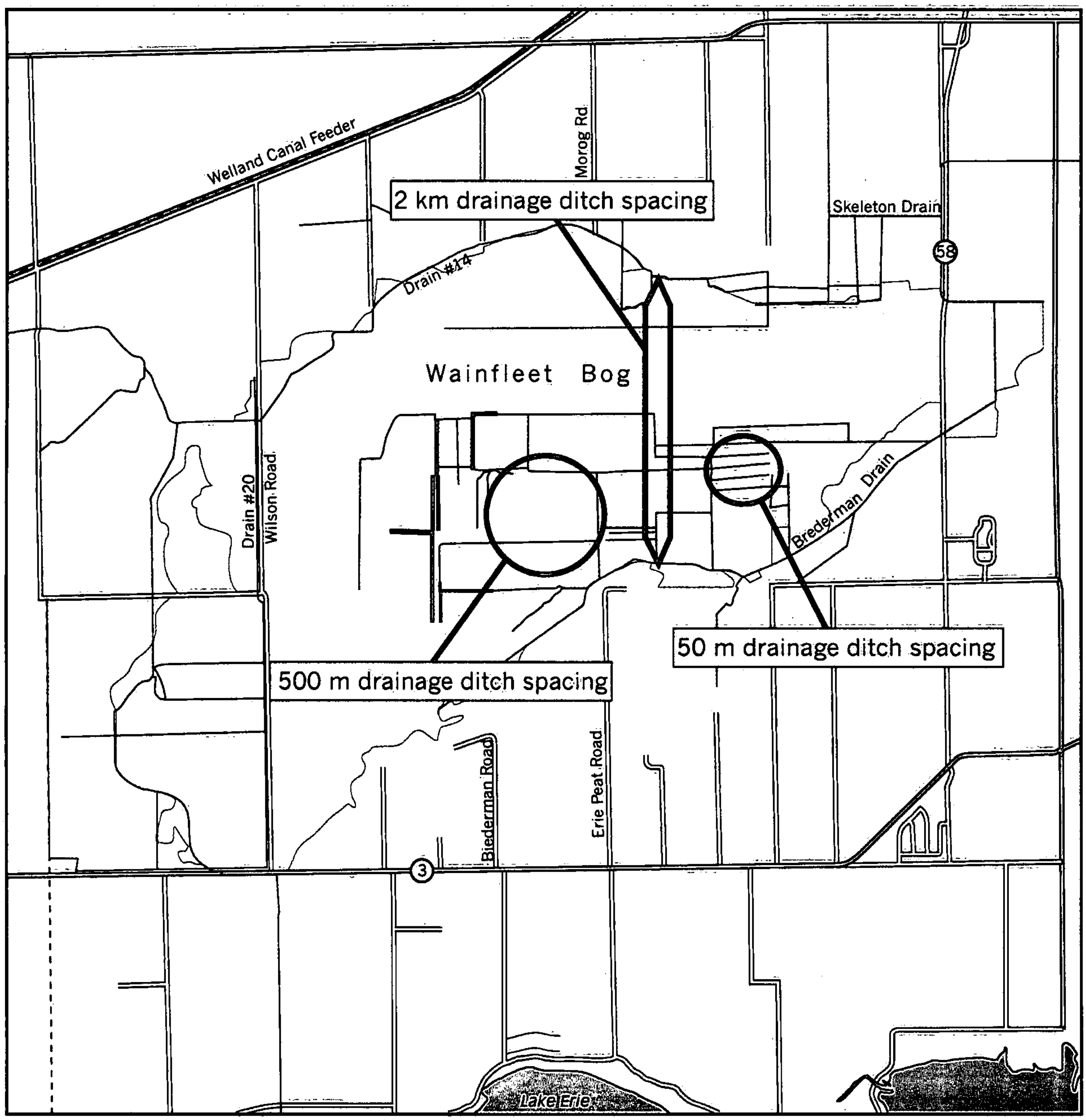


Figure 2 - Schematic of the three scales used in the ditch spacing scenarios

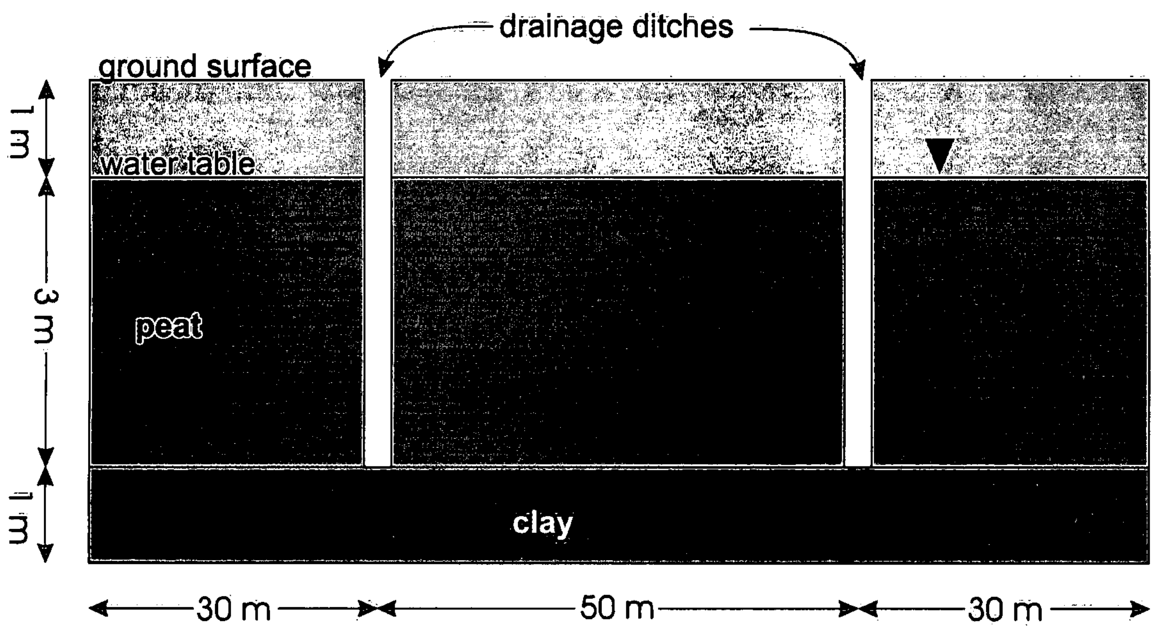


Figure 3 - Schematic of 2D cross-section with 50-metre ditch spacing.

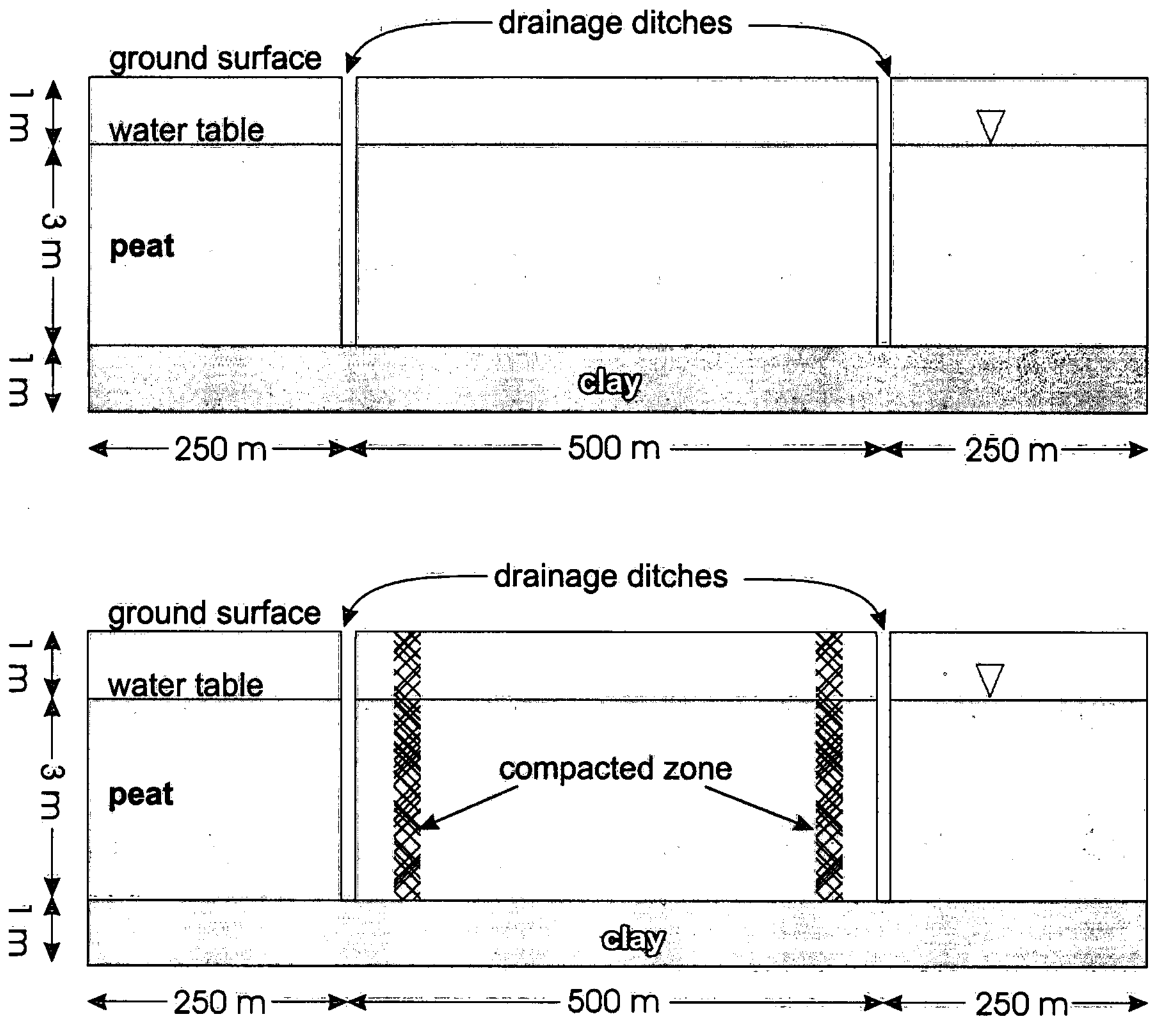


Figure 4 - Schematic of 2D cross section with 500-metre ditch spacing.

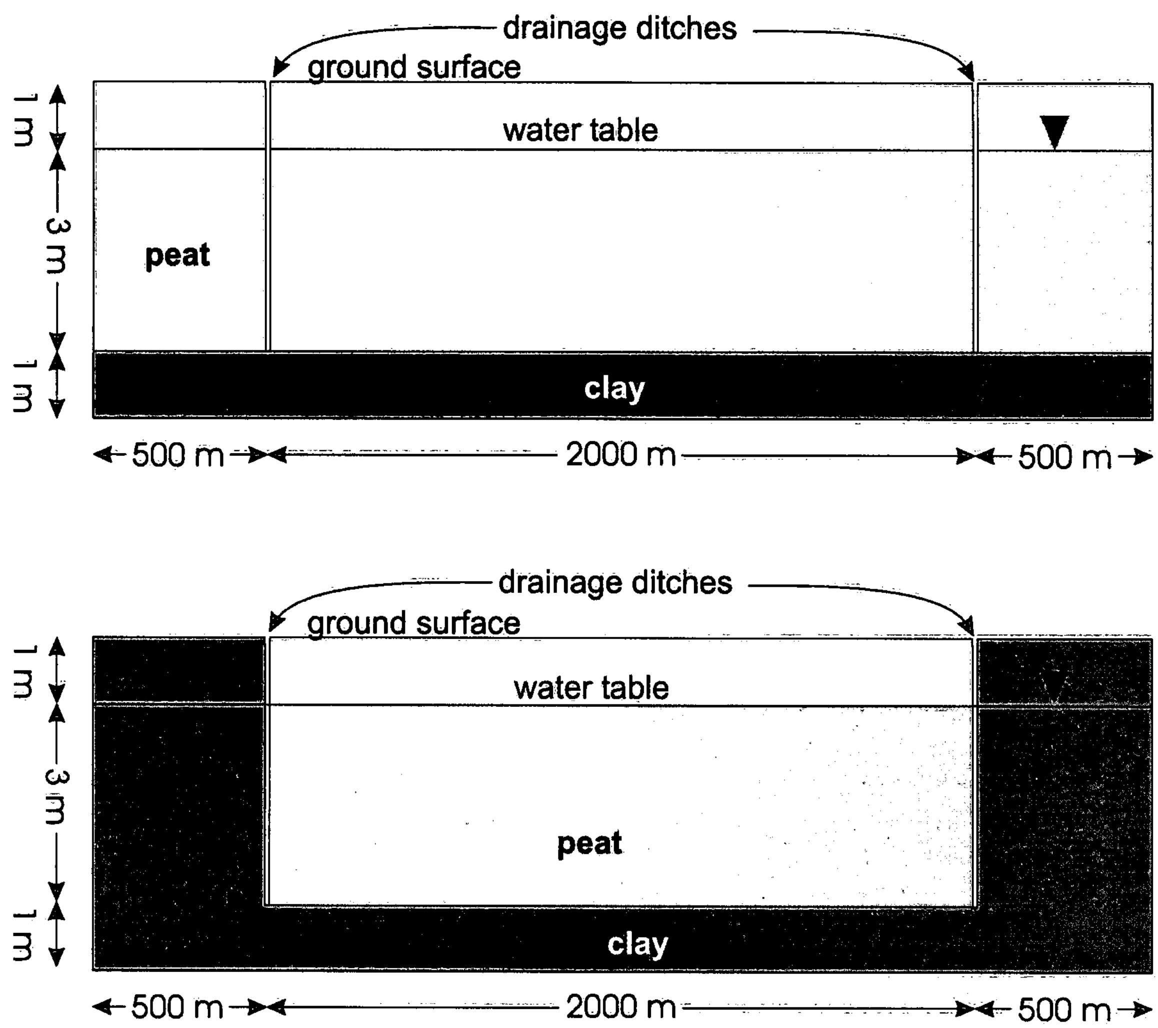


Figure 5 - Schematic of 2D cross section with 2000-metre ditch spacing.

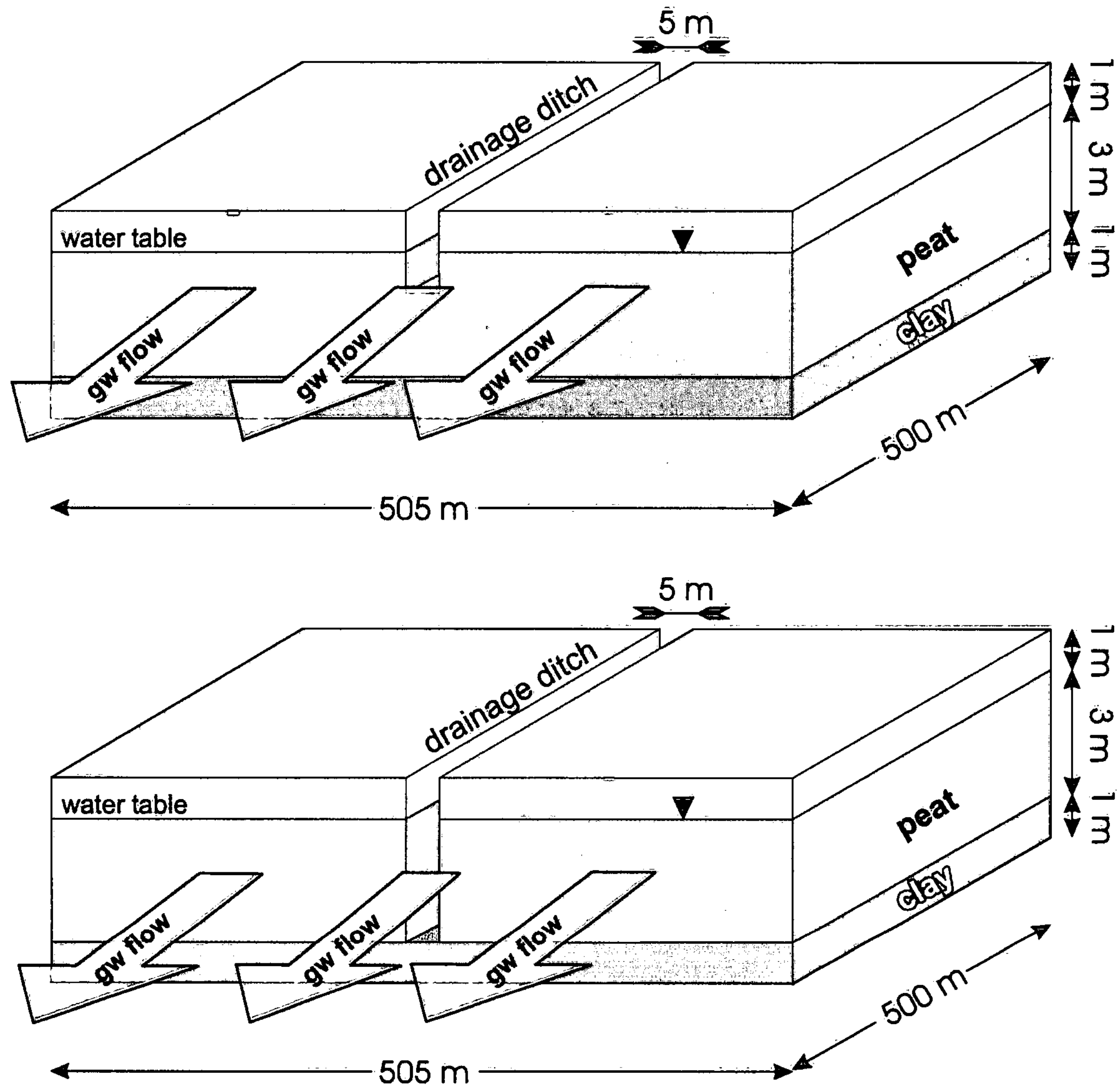


Figure 6 - Schematic of peat used to simulate ditch-closure scenarios.

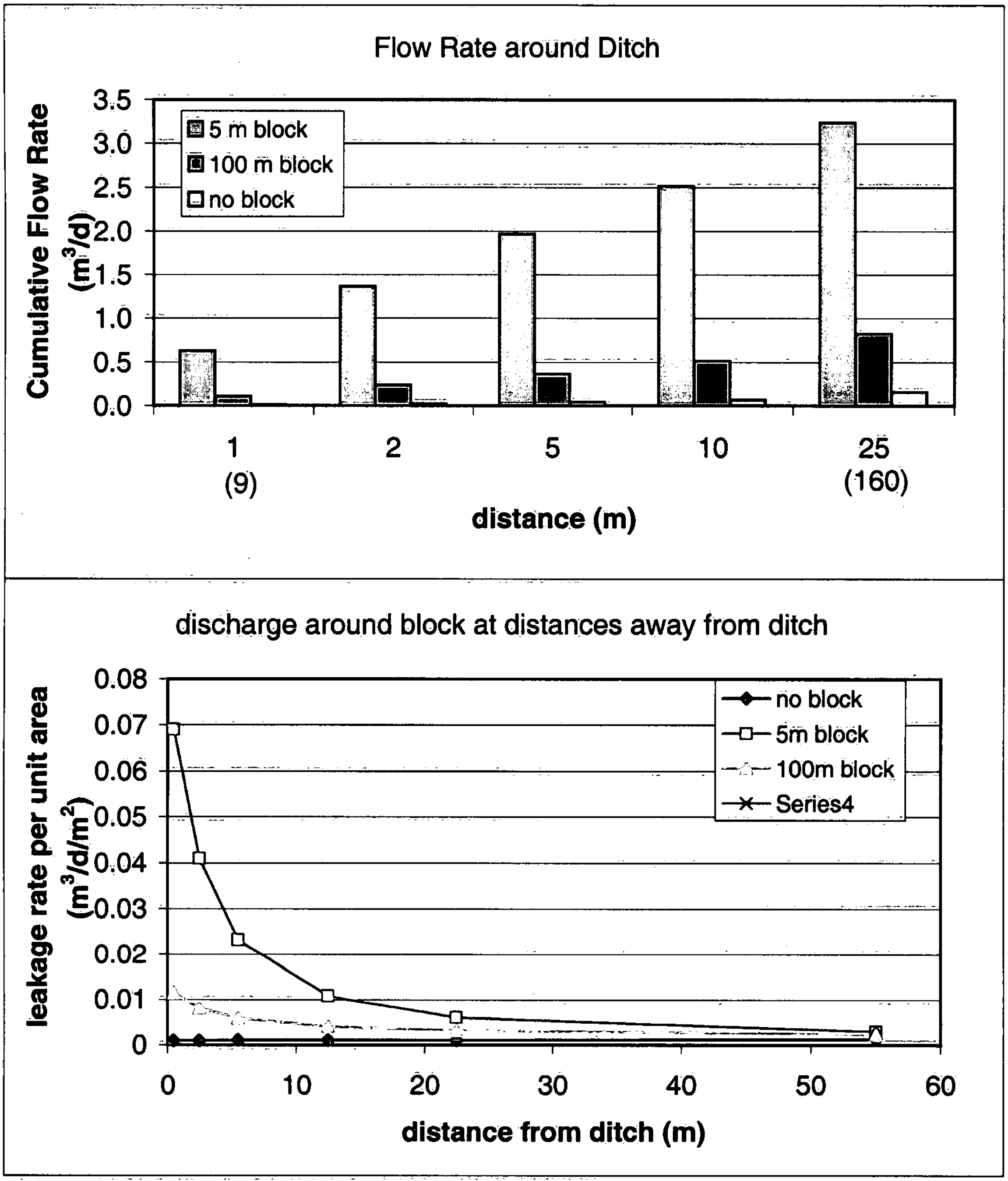


Figure 7 - Analysis of leakage around ditch blockage. (a) volume of flow versus increasing distances from ditch, (b) flow per unit area at specific distances from ditch.

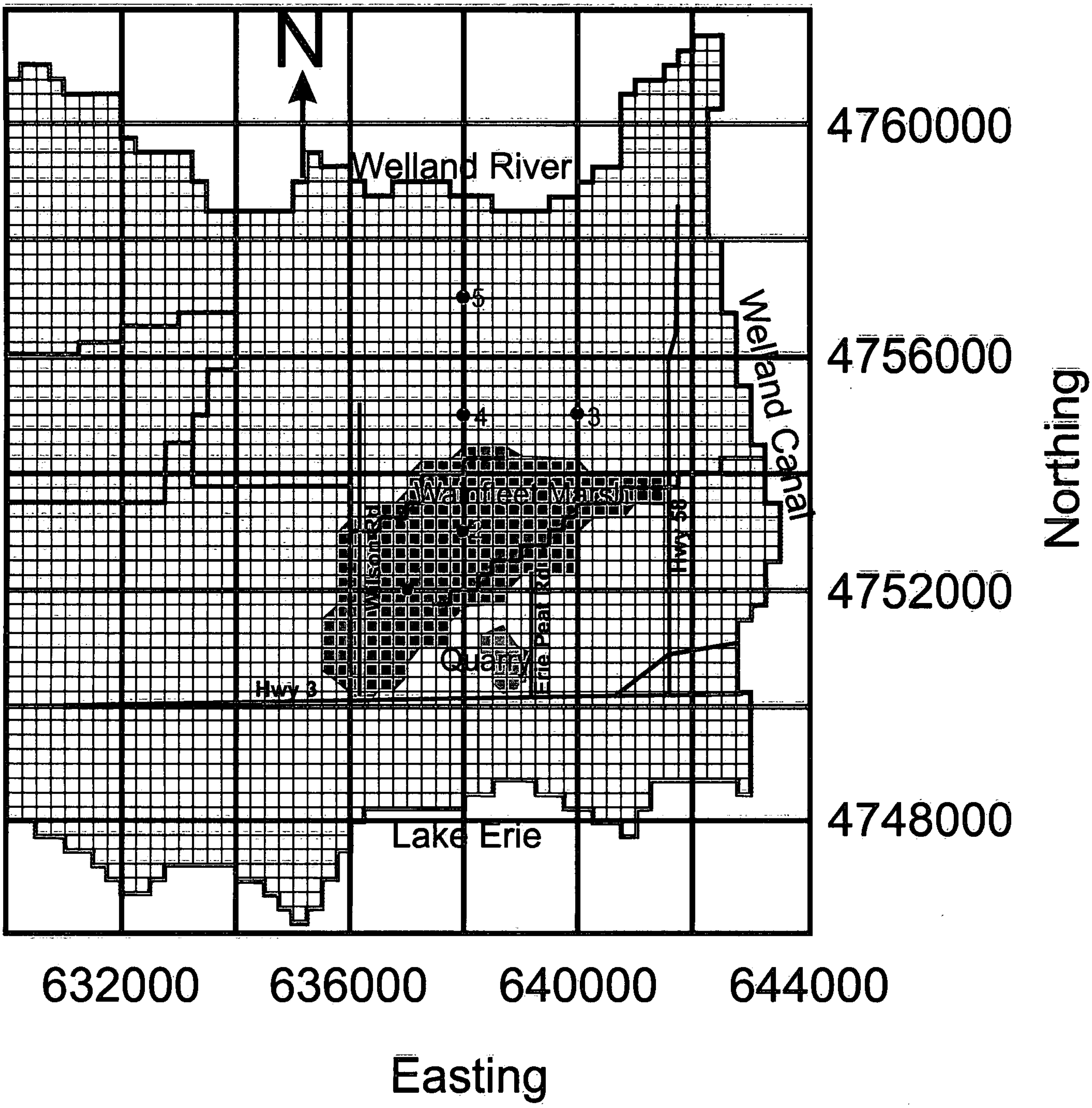


Figure 8 - Plan view of 3D domain for regional impact simulations. Surficial boundary conditions are shown in blue (including main drainage canals) Monitoring wells are shown in red.

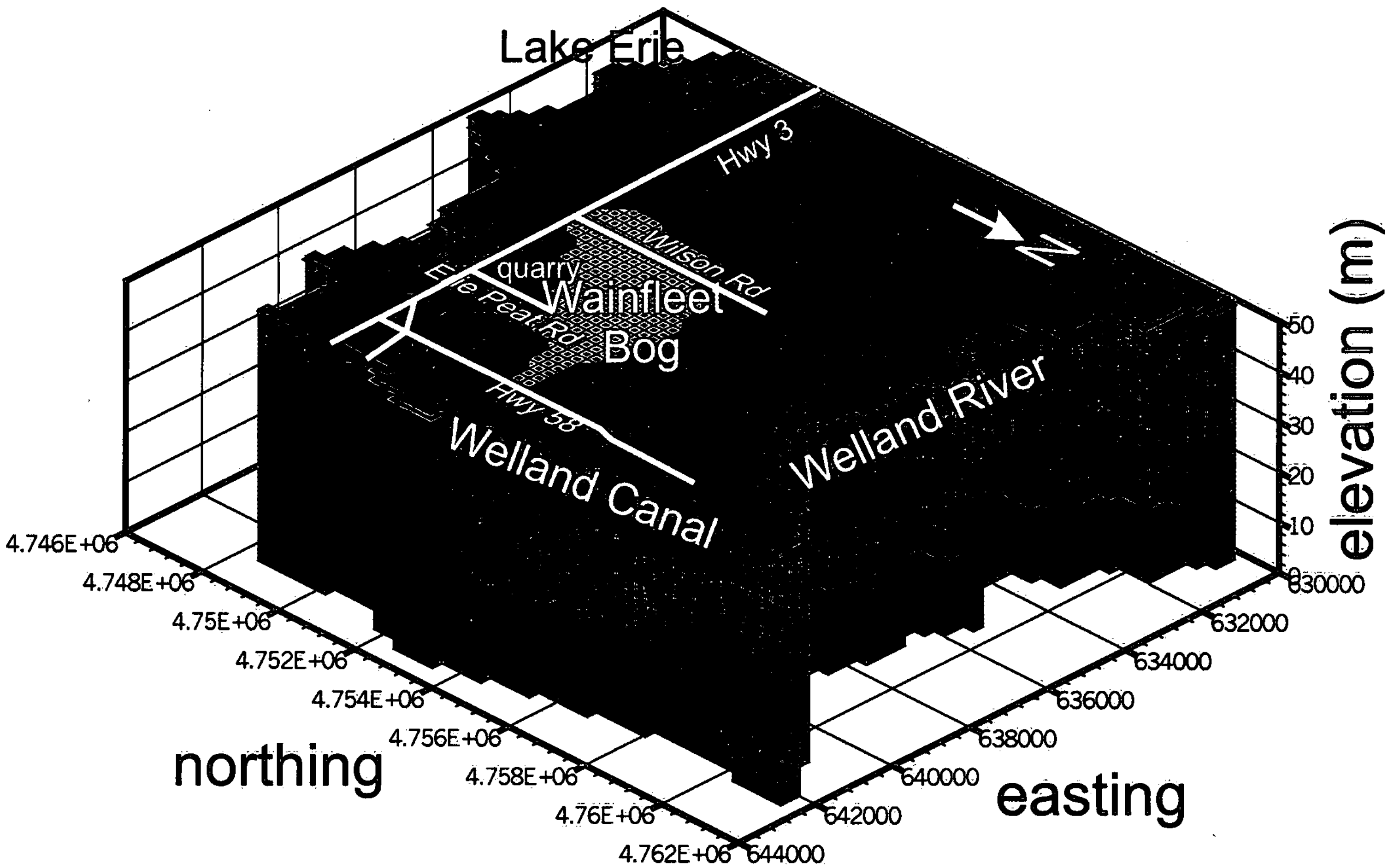


Figure 9: 3D perspective of the 3D domain for the regional impact simulations. The three stratigraphic units are shown:- blue - bedrock; green - clay; red - peat.

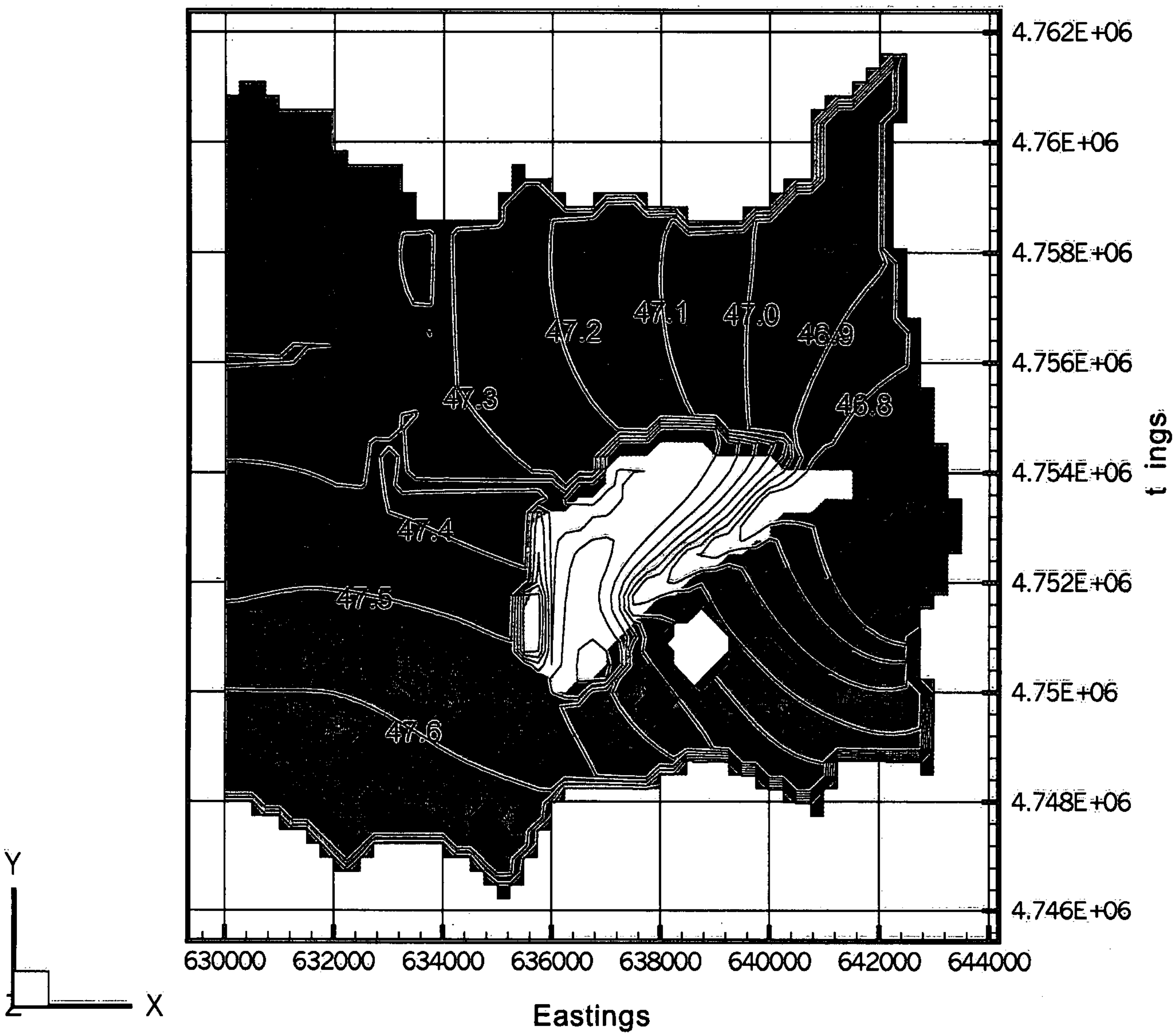


Figure 10 - Simulated elevation of the water table under pre-restorative conditions.

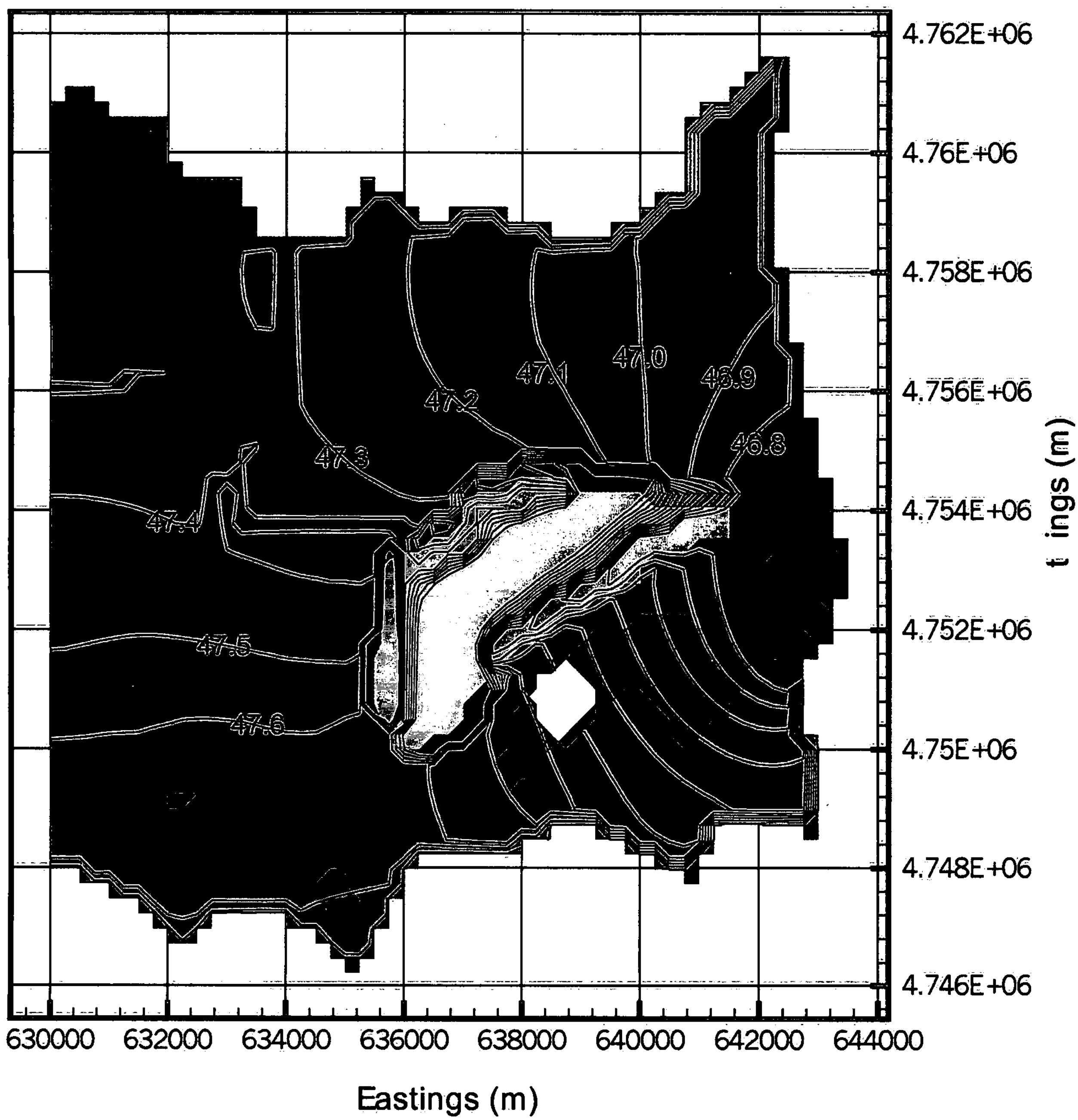


Figure 11 - Simulated elevation of the water table after a 10-year, 1-metre rise.

Appendix 1:

Estimate of Evapotranspiration from Birch Trees

Birch Transpiration (Initial Notes - Mark Browning)

There are two types of information available from the literature. The first is based on measurements made on individual trees, often seedlings grown in sealed pots or lysimeters where weight changes can be measured. Other techniques include enclosing whole trees in plastic tents, or cutting and instantly weighing branches to measure loss rate during the first few minutes. All these methods give a transpiration rate in kg H_2O/m^2 leaf area/day or something similar. The problem with these measurements is in trying to extrapolate to entire stands of trees. To calculate transpiration on a watershed basis the water balance equation is used often in a paired catchment type design. Other variables in the equation are measured and the transpiration rate can then be calculated. This type of measurement gives a transpiration rate as a linear measure (e.g. cm) which indicates a uniform depth of water over the entire basin.

I have both types of measurements. Generally, for deciduous trees of the temperate zone the literature gives individual transpiration rates of:

1. 3-4 kg H_2O/day for young trees approx. 3 m height, with leaf area of 3-5 m^2.
2. 30-70 kg H_2O/day for trees in dense forests, 12 m height, with leaf area 30-55 m^2.
3. 130-140 kg H_2O/day for loose-crown trees of 12 m height, with leaf area of 60-70 m^2.

However, birch (and aspen as well) have very high rates of transpiration in comparison to other northern temperate hardwood species. In talking with our tree physiologist at the Ontario Forest Research Institute she felt that for relatively young trees (category 1 above) that a rate closer to 10-11 kg H_2O/day could be used for birch and aspen. She also noted that the greater the tree density the lower the rate of transpiration per individual tree. I guess it would be a good idea to get some measurements on tree age, height and density from our vegetation plots this summer Kim.

The second type of measurement (linear measure on a stand basis) comes from talking with another OFRI researcher who has worked extensively in southern Ontario and along the north shore of Lake Huron on conifer water relations. He gave me average rates of transpiration for white birch stands as follows:

April-May	2-3 mm/day
May-June	3.5-4 mm/day
June-July	5 mm/day (at peak seasonal temperature and minimum humidity)
July-August	3.5-4 mm/day
August-Sept.	2-3 mm/day

Values might go up to 7-8 mm/day at peak temperatures on xeric sites with low relative humidity. However, I assume most of the Wainfleet bog would be more humid than this even at peak summer temperatures.

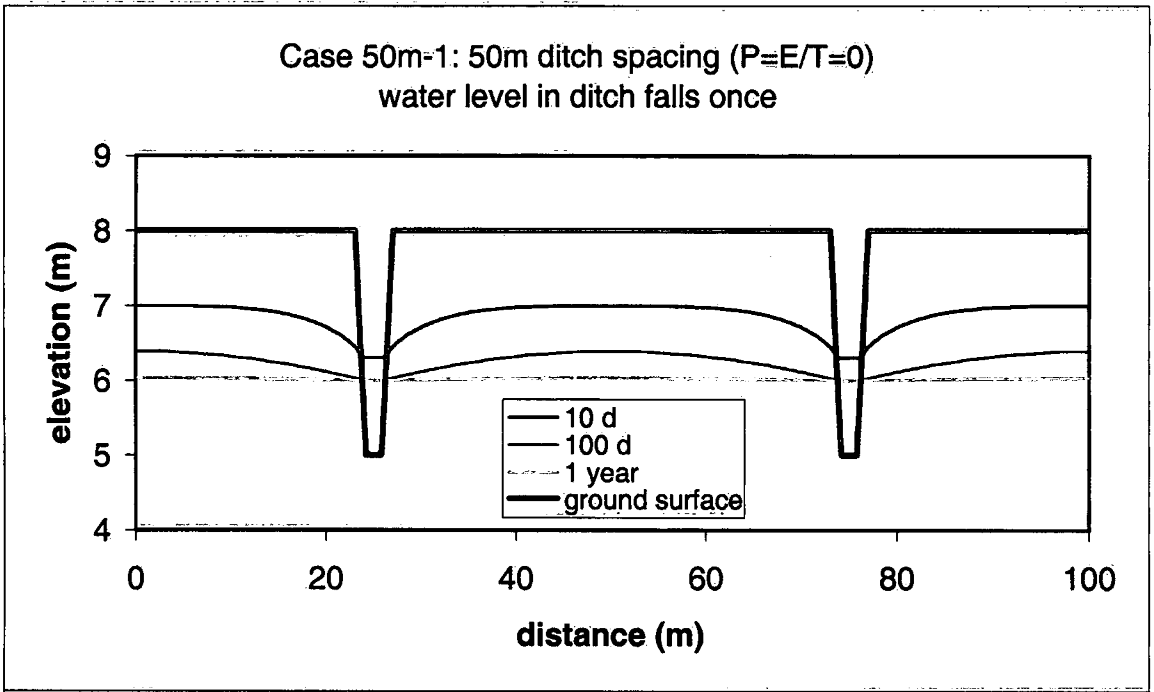
Hope this helps in the hydrology modeling. My initial calculations indicate that once the birch canopy is killed that a lot of extra water would be available for below ground storage - in the order of 5 billion liters H_2O per year (assuming the whole site other than the peat mined area is now treed with young birch which is probably not true but its a first rough calculation!

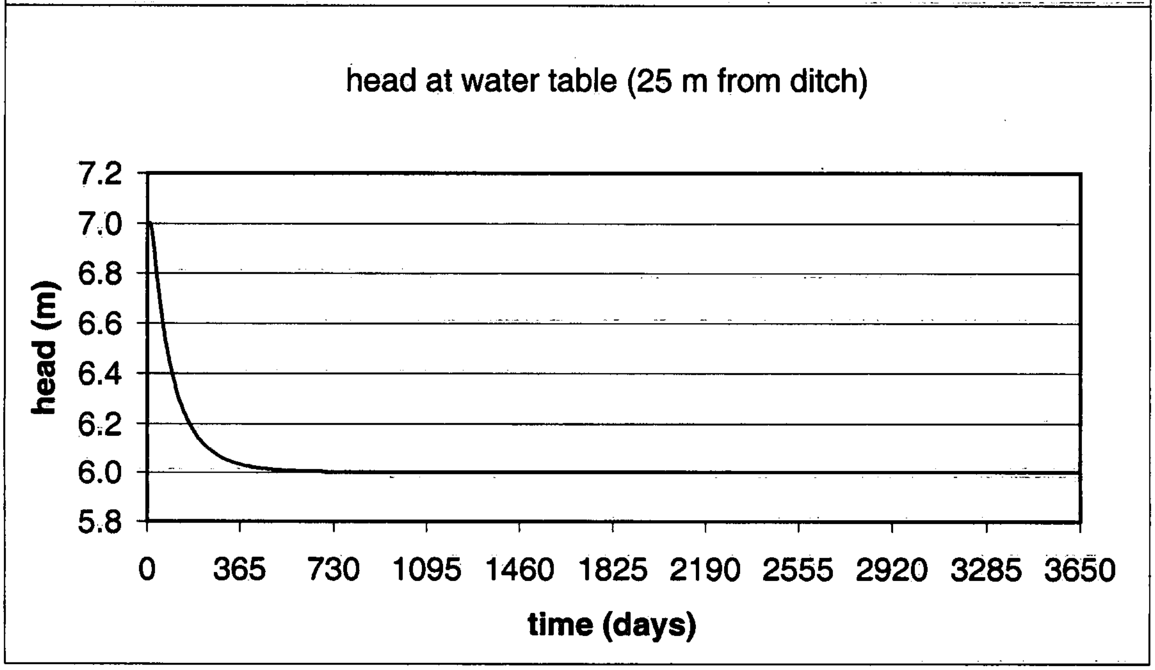
Looking forward to field work in the bog.

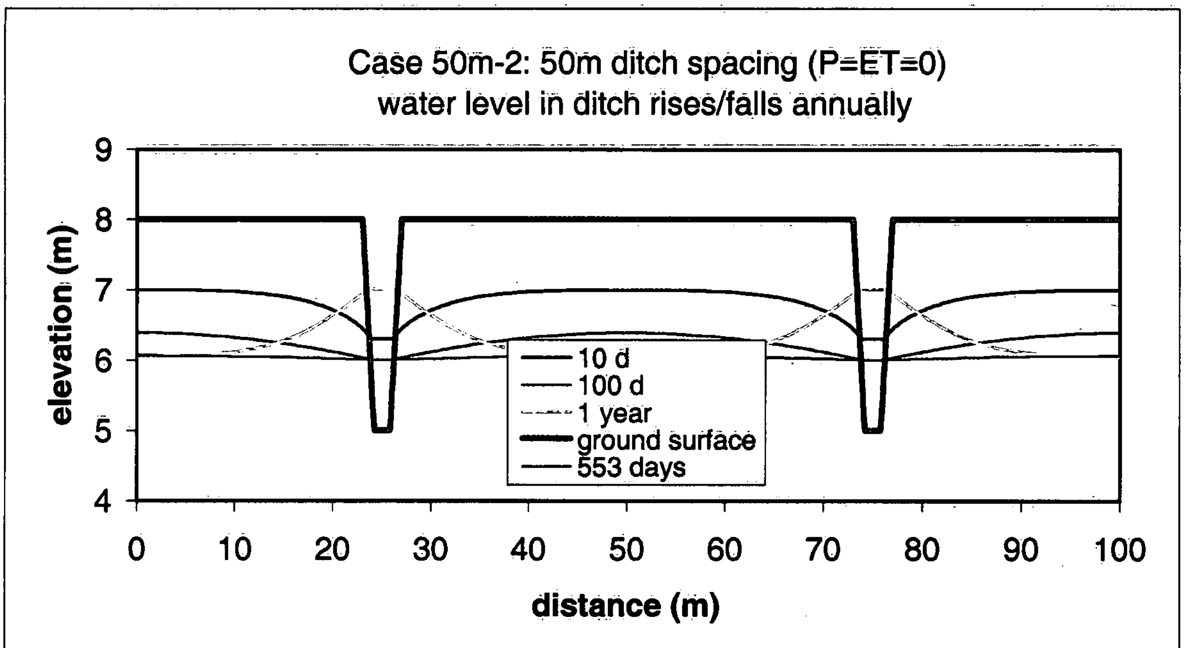
Mark

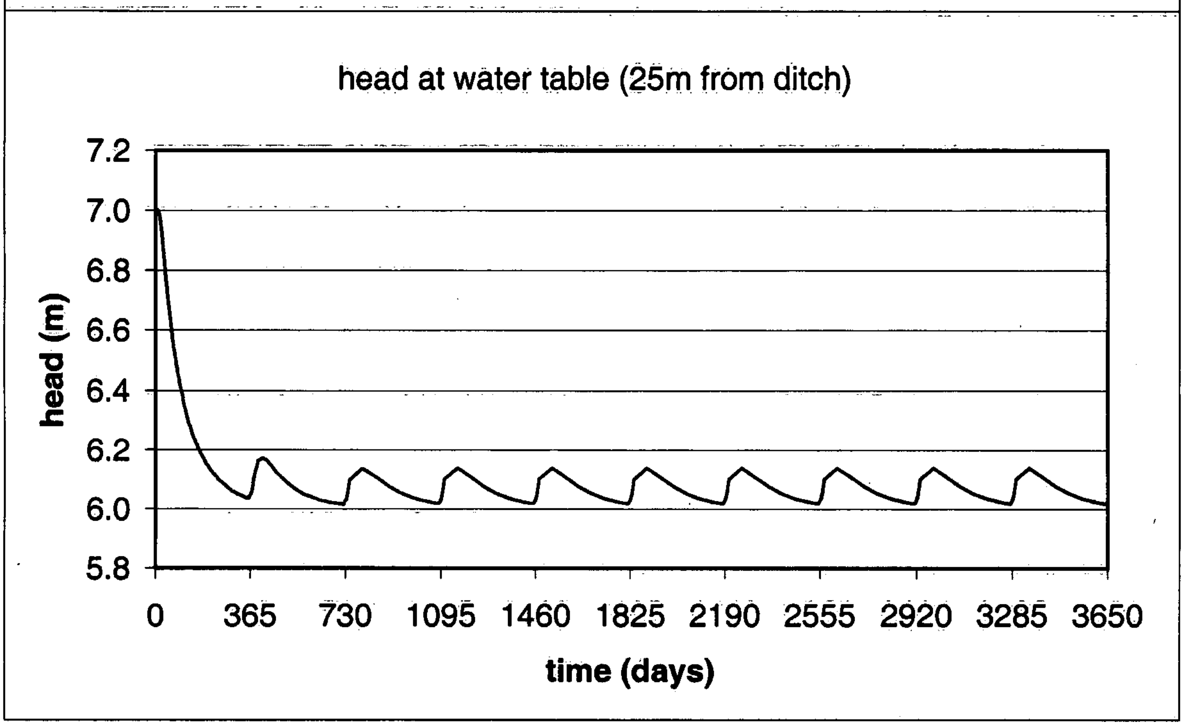
Appendix 2:

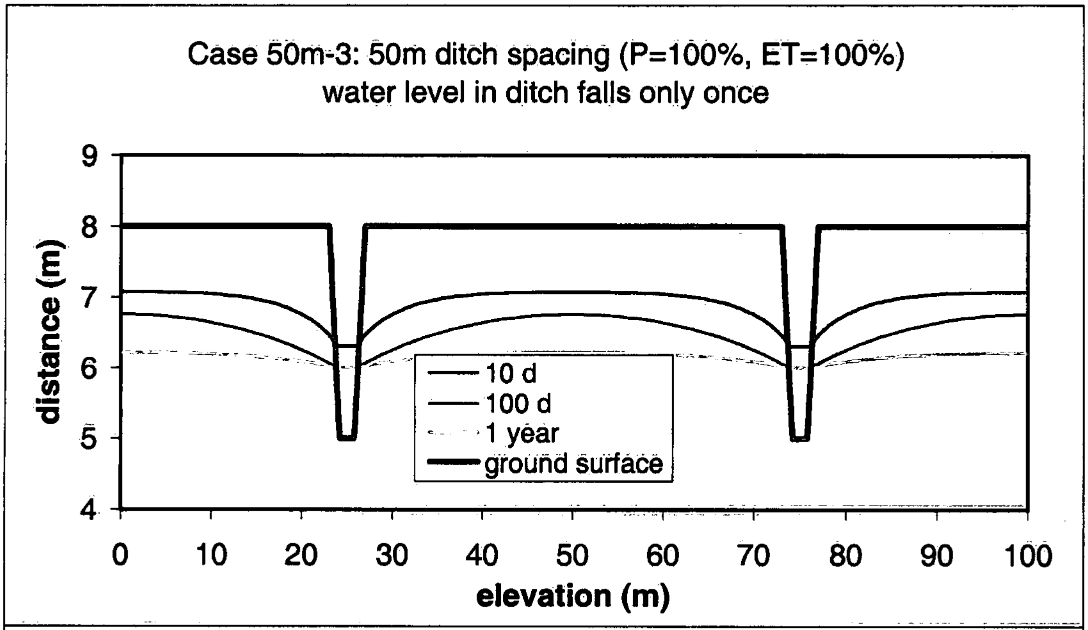
Impact of Drainage Ditches with a 50m Spacing on the Water Table

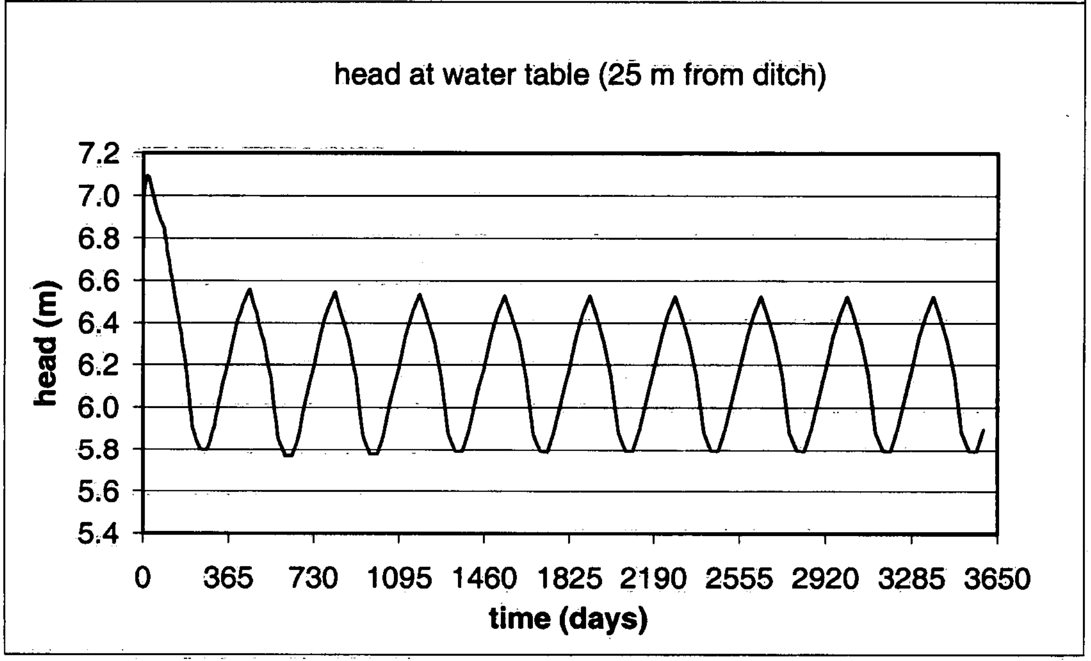

Case 50m-1: 50m ditch spacing (P=E/T=0)
water level in ditch falls once
elevation (m)
9
8
7
6
5
4
0
20
40
60
80
100
distance (m)
10 d
100 d
1 year
ground surface

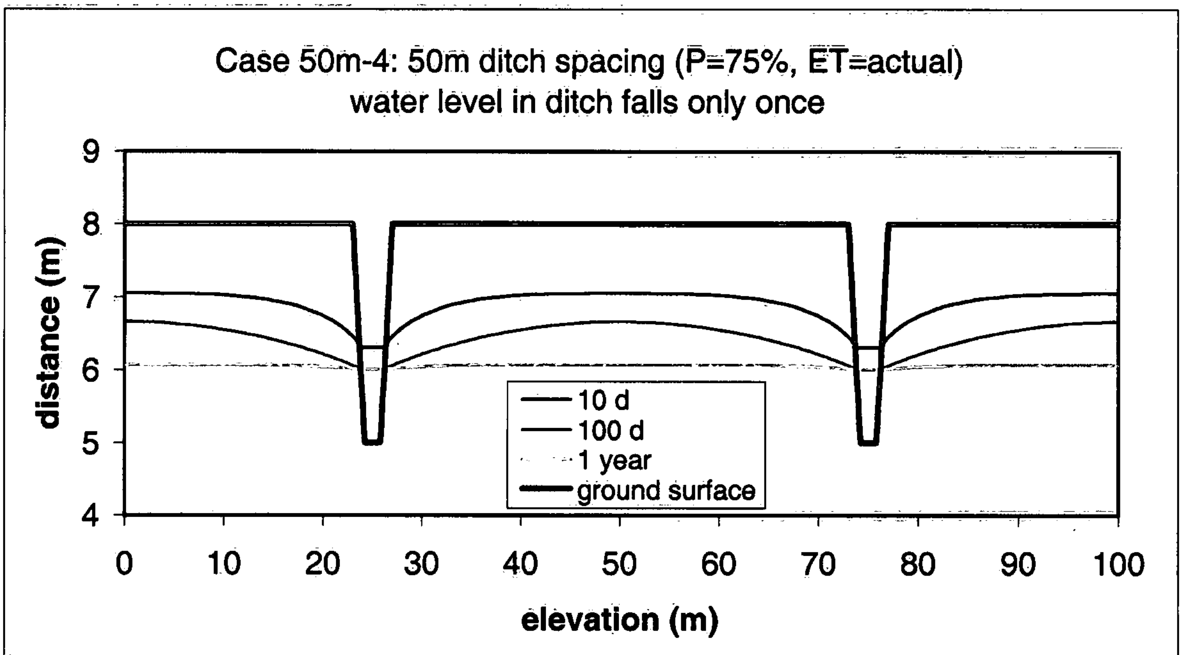

head at water table (25 m from ditch)
head (m)
7.2
7.0
6.8
6.6
6.4
6.2
6.0
5.8
0
365
730
1095
1460
1825
2190
2555
2920
3285
3650
time (days)

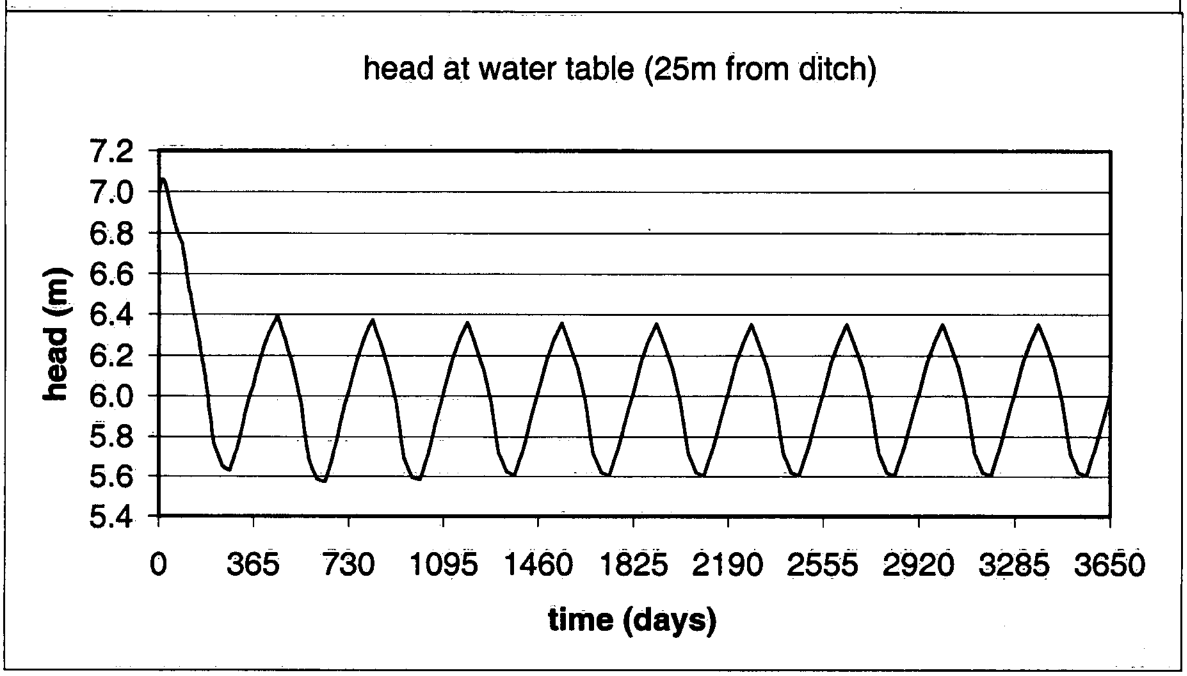

Case 50m-2: 50m ditch spacing (P=ET=0)
water level in ditch rises/falls annually
elevation (m)
distance (m)
10 d
100 d
1 year
ground surface
553 days
9
8
7
6
5
4
0
10
20
30
40
50
60
70
80
90
100

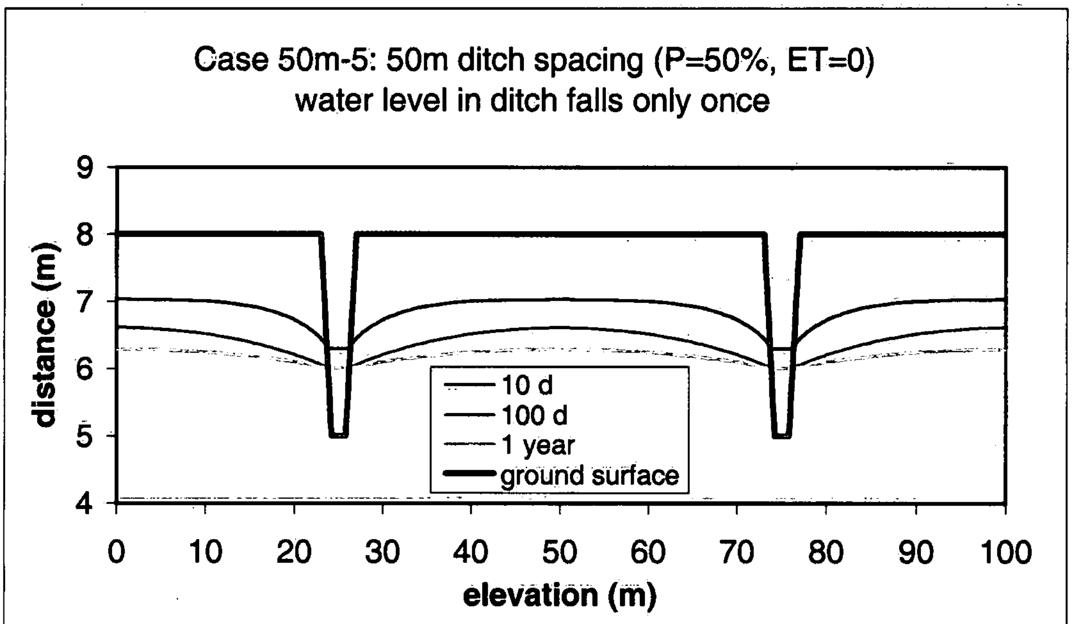

head at water table (25m from ditch)
head (m)
time (days)
7.2
7.0
6.8
6.6
6.4
6.2
6.0
5.8
0
365
730
1095
1460
1825
2190
2555
2920
3285
3650

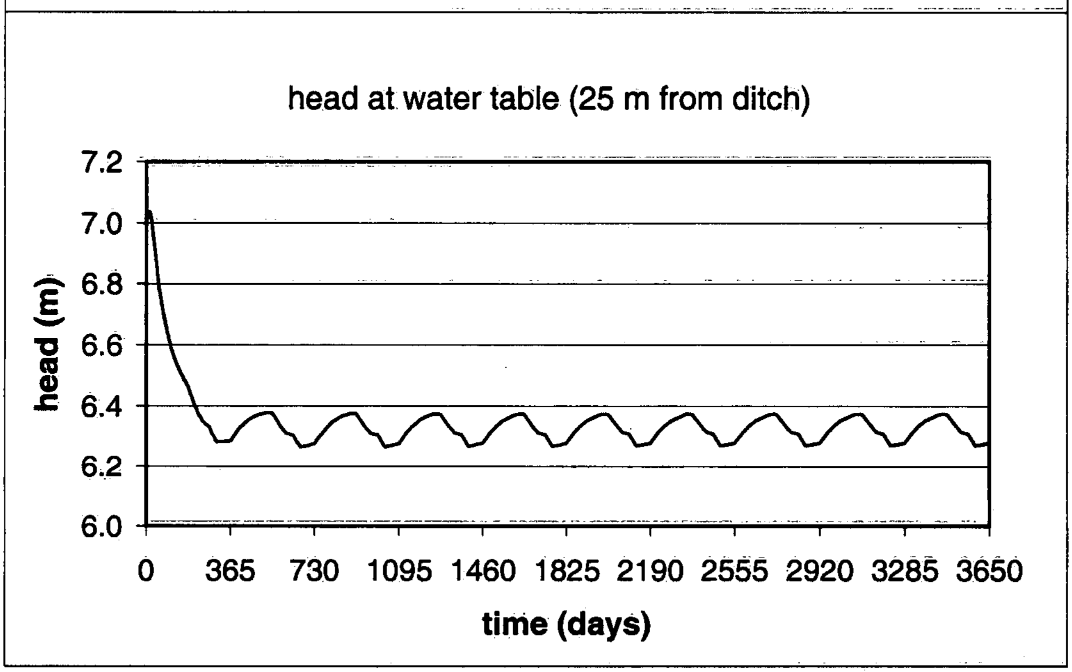

Case 50m-3: 50m ditch spacing (P=100%, ET=100%)
water level in ditch falls only once
distance (m)
elevation (m)
10 d
100 d
1 year
ground surface
9
8
7
6
5
4
0
10
20
30
40
50
60
70
80
90
100

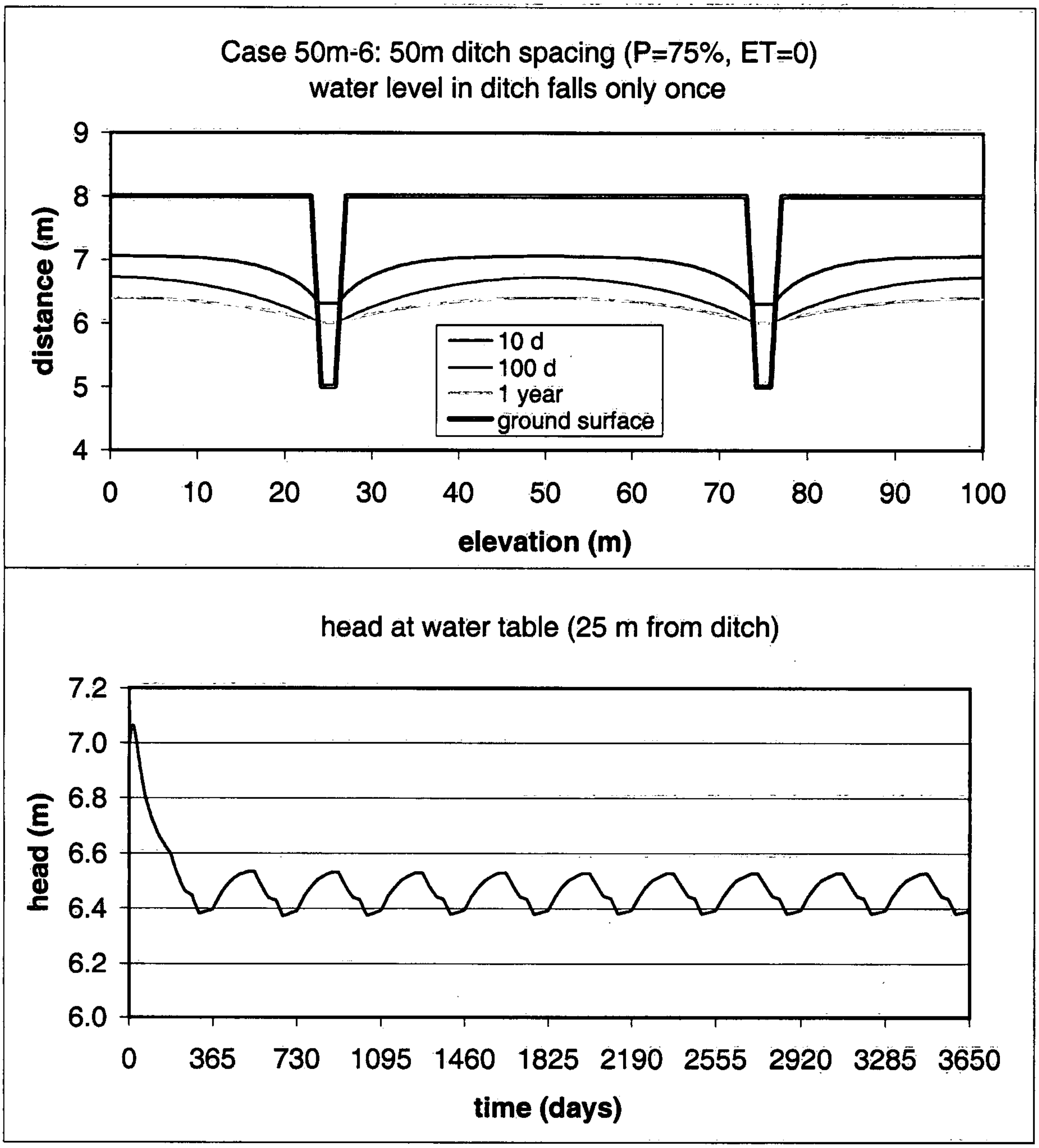

head at water table (25 m from ditch)
head (m)
time (days)
7.2
7.0
6.8
6.6
6.4
6.2
6.0
5.8
5.6
5.4
0
365
730
1095
1460
1825
2190
2555
2920
3285
3650

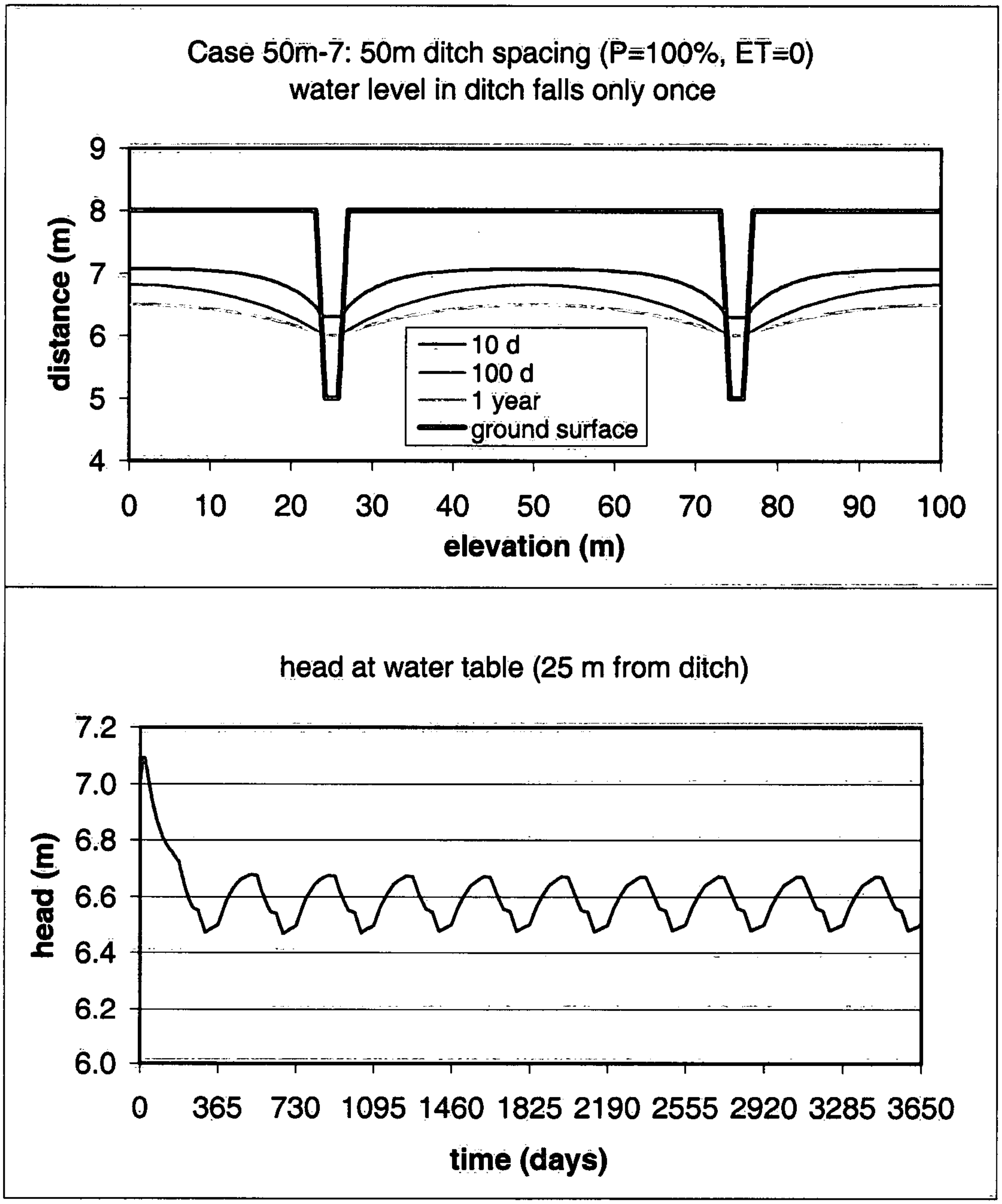

Case 50m-4: 50m ditch spacing (P=75%, ET=actual)
water level in ditch falls only once
9
8
7
6
5
4
distance (m)
10 d
100 d
1 year
ground surface
0
10
20
30
40
50
60
70
80
90
100
elevation (m)


head at water table (25m from ditch)
7.2
7.0
6.8
6.6
6.4
6.2
6.0
5.8
5.6
5.4
head (m)
0
365
730
1095
1460
1825
2190
2555
2920
3285
3650
time (days)


Case 50m-5: 50m ditch spacing (P=50%, ET=0)
water level in ditch falls only once
distance (m)
elevation (m)
10 d
100 d
1 year
ground surface
9
8
7
6
5
4
0
10
20
30
40
50
60
70
80
90
100

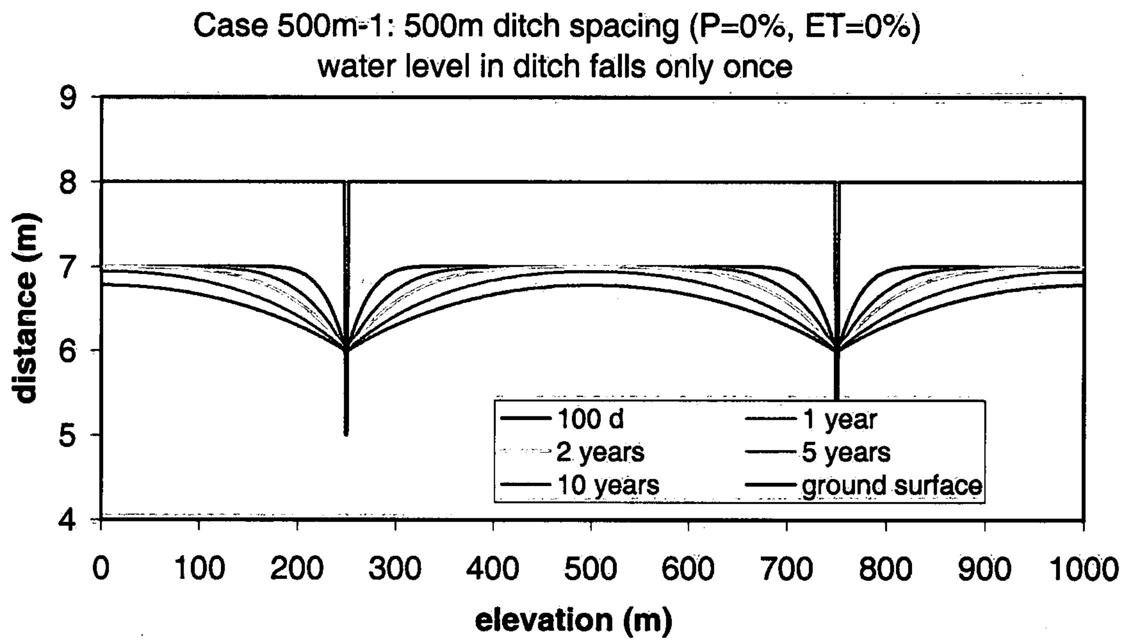

head at water table (25 m from ditch)
head (m)
time (days)
7.2
7.0
6.8
6.6
6.4
6.2
6.0
0
365
730
1095
1460
1825
2190
2555
2920
3285
3650

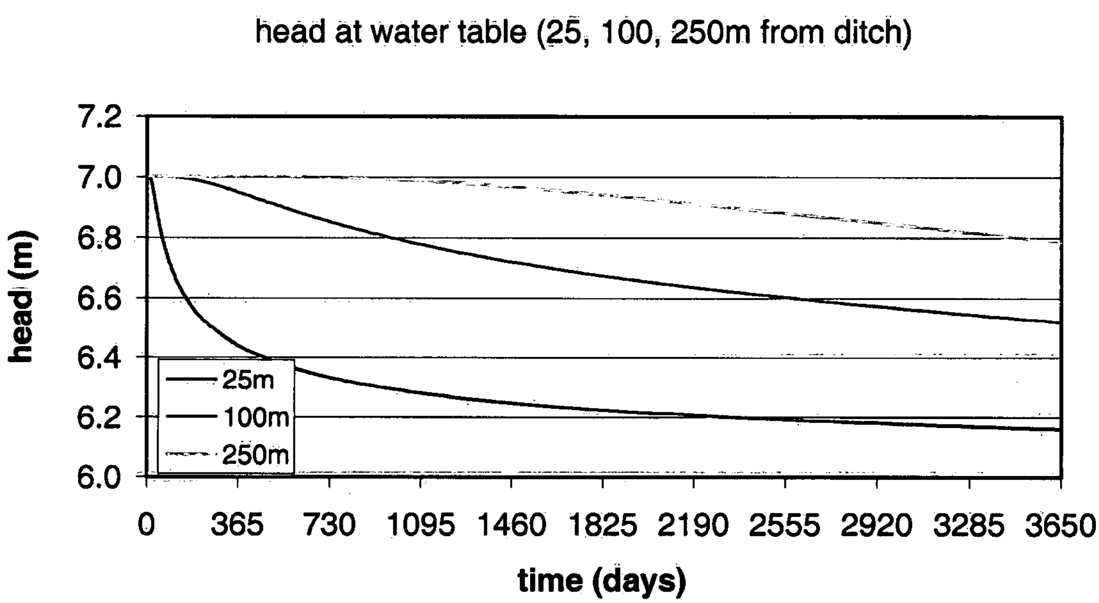

Case 50m-6: 50m ditch spacing (P=75%, ET=0)
water level in ditch falls only once
distance (m)
elevation (m)
10 d
100 d
1 year
ground surface
9
8
7
6
5
4
0
10
20
30
40
50
60
70
80
90
100
head at water table (25 m from ditch)
head (m)
time (days)
7.2
7.0
6.8
6.6
6.4
6.2
6.0
0
365
730
1095
1460
1825
2190
2555
2920
3285
3650

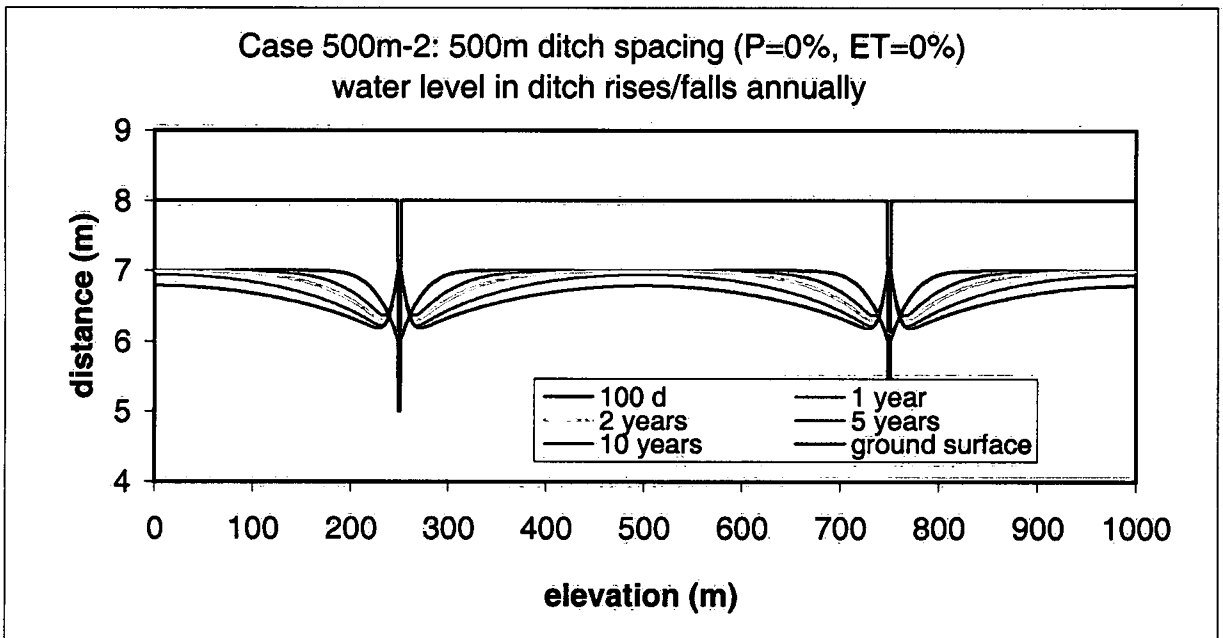

Case 50m-7: 50m ditch spacing (P=100%, ET=0)
water level in ditch falls only once
distance (m)
elevation (m)
10 d
100 d
1 year
ground surface
9
8
7
6
5
4
0
10
20
30
40
50
60
70
80
90
100
head at water table (25 m from ditch)
head (m)
time (days)
7.2
7.0
6.8
6.6
6.4
6.2
6.0
0
365
730
1095
1460
1825
2190
2555
2920
3285
3650

Appendix 3:

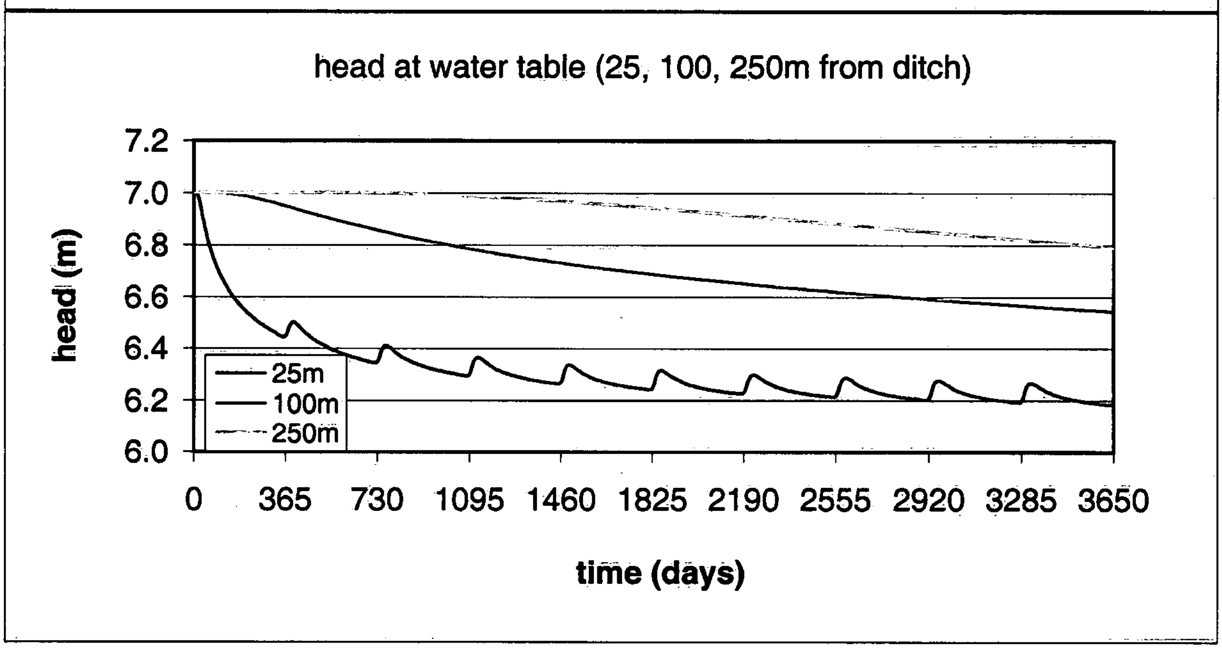
Impact of Drainage Ditches with a 500m Spacing on the Water Table


Case 500m-1: 500m ditch spacing (P=0%, ET=0%)
water level in ditch falls only once
distance (m)
9
8
7
6
5
4
0
100
200
300
400
500
600
700
800
900
1000
elevation (m)
100 d
1 year
2 years
5 years
10 years
ground surface

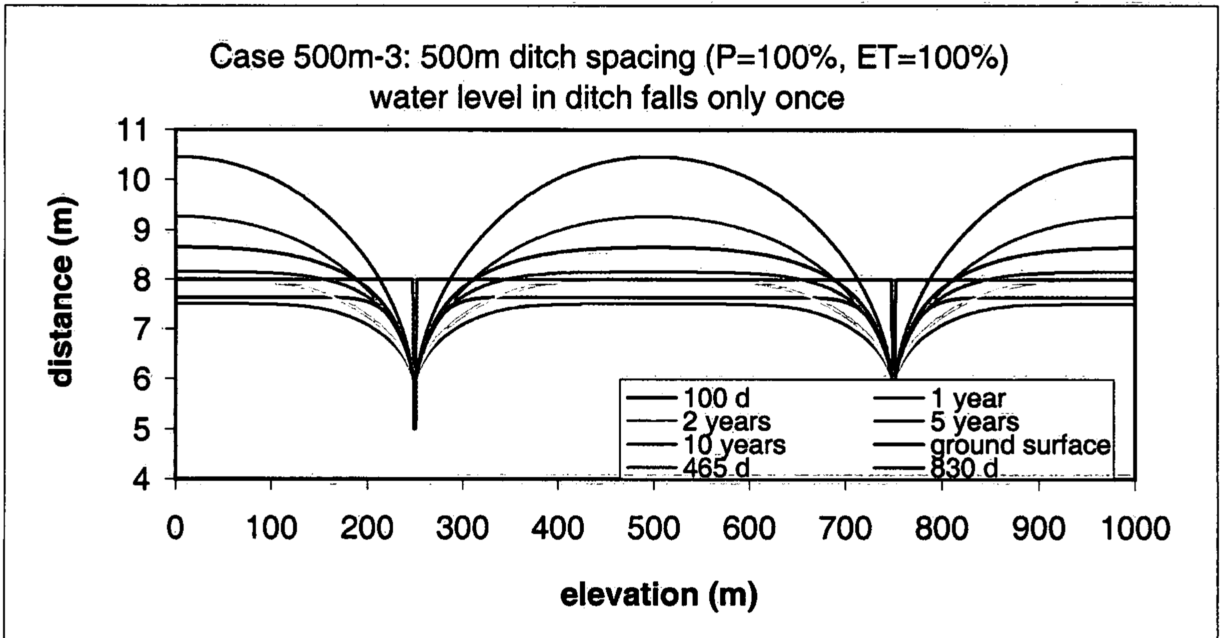

head at water table (25, 100, 250m from ditch)
head (m)
7.2
7.0
6.8
6.6
6.4
6.2
6.0
0
365
730
1095
1460
1825
2190
2555
2920
3285
3650
time (days)
25m
100m
250m



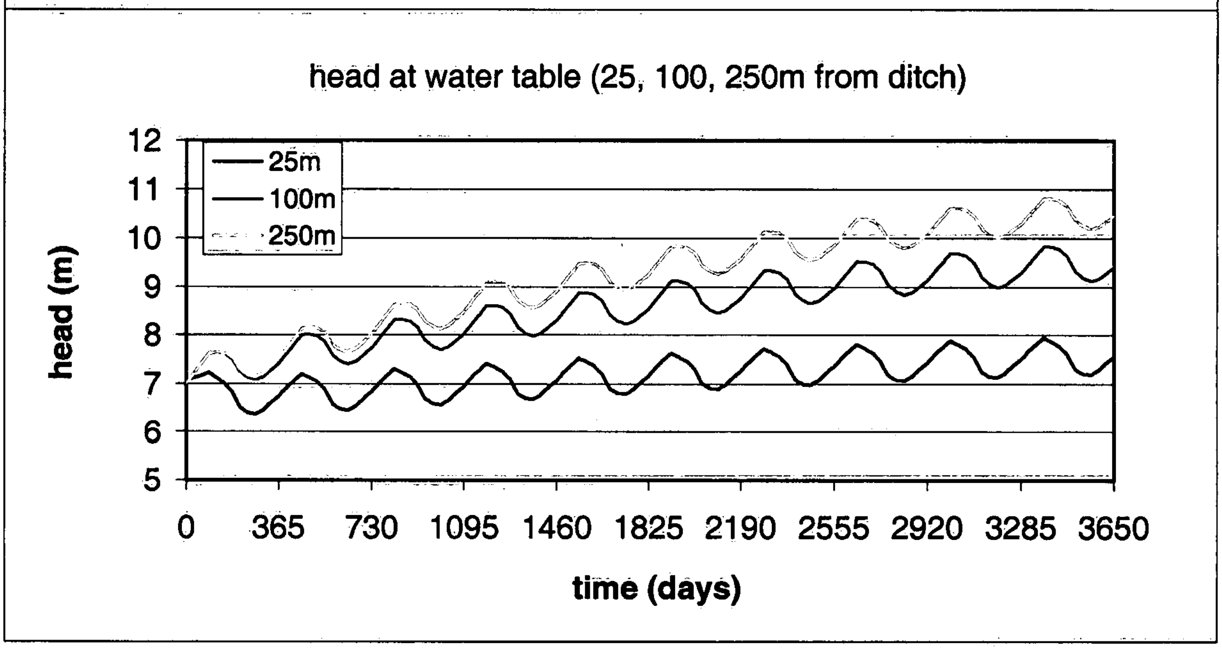
Case 500m-2: 500m ditch spacing (P=0%, ET=0%)
water level in ditch rises/falls annually
distance (m)
elevation (m)
9
8
7
6
5
4
0
100
200
300
400
500
600
700
800
900
1000
100 d
1 year
2 years
5 years
10 years
ground surface



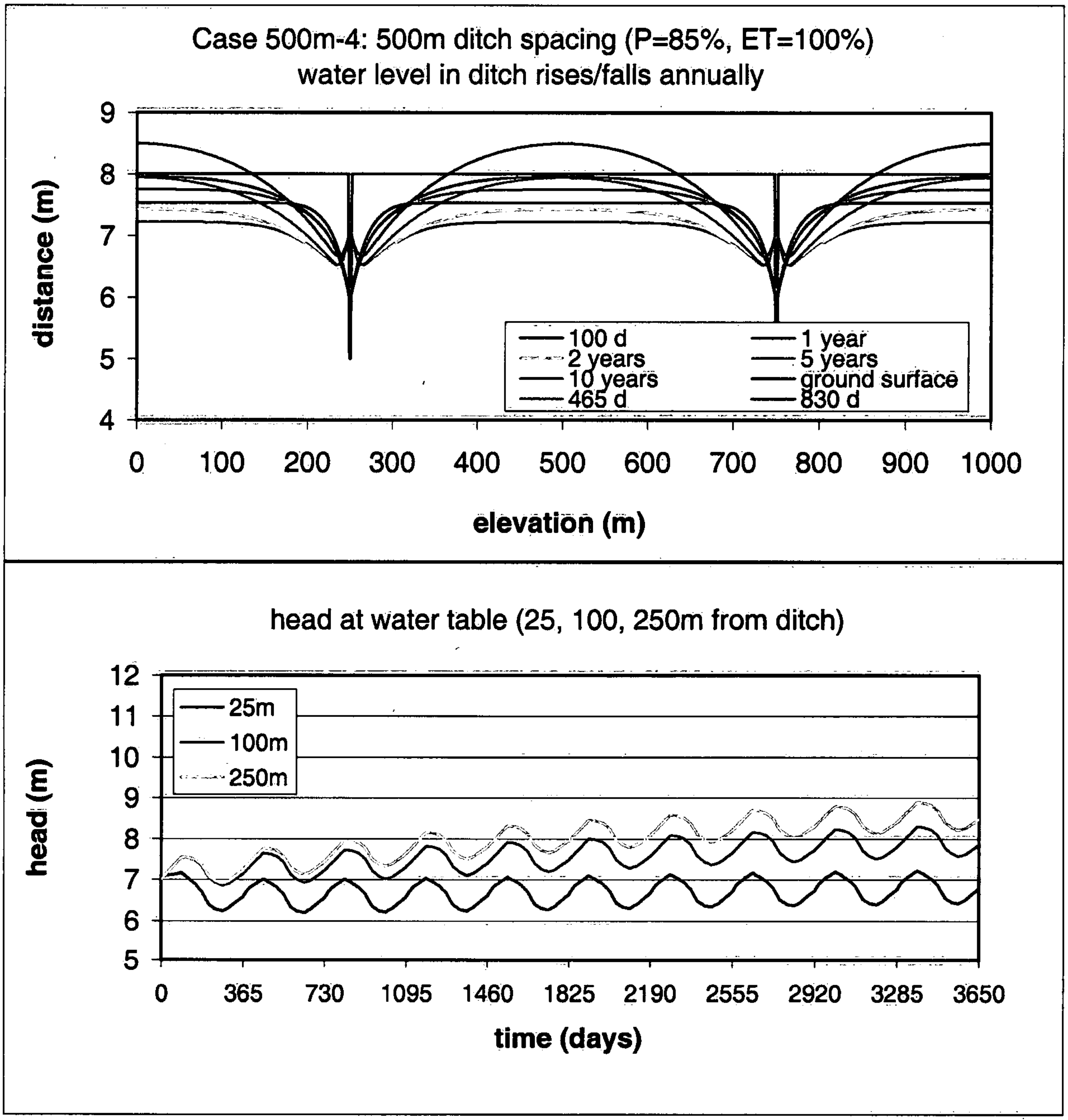
head at water table (25, 100, 250m from ditch)
head (m)
time (days)
7.2
7.0
6.8
6.6
6.4
6.2
6.0
0
365
730
1095
1460
1825
2190
2555
2920
3285
3650
25m
100m
250m



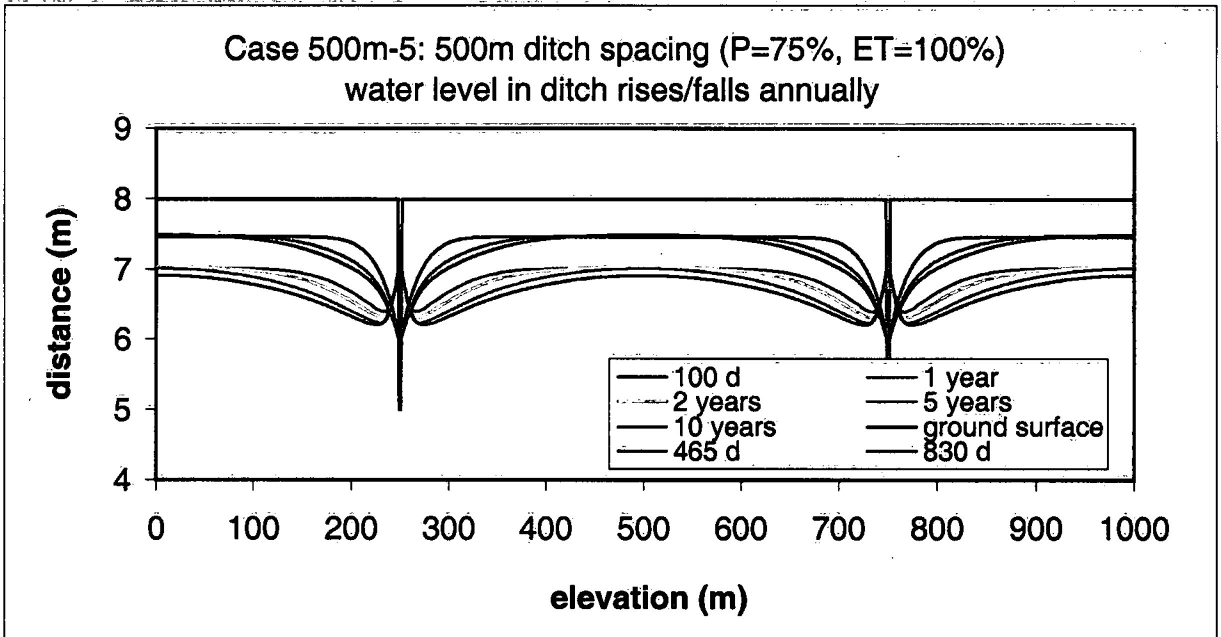
Case 500m-3: 500m ditch spacing (P=100%, ET=100%)
water level in ditch falls only once
distance (m)
elevation (m)
100 d
1 year
2 years
5 years
10 years
ground surface
465 d
830 d



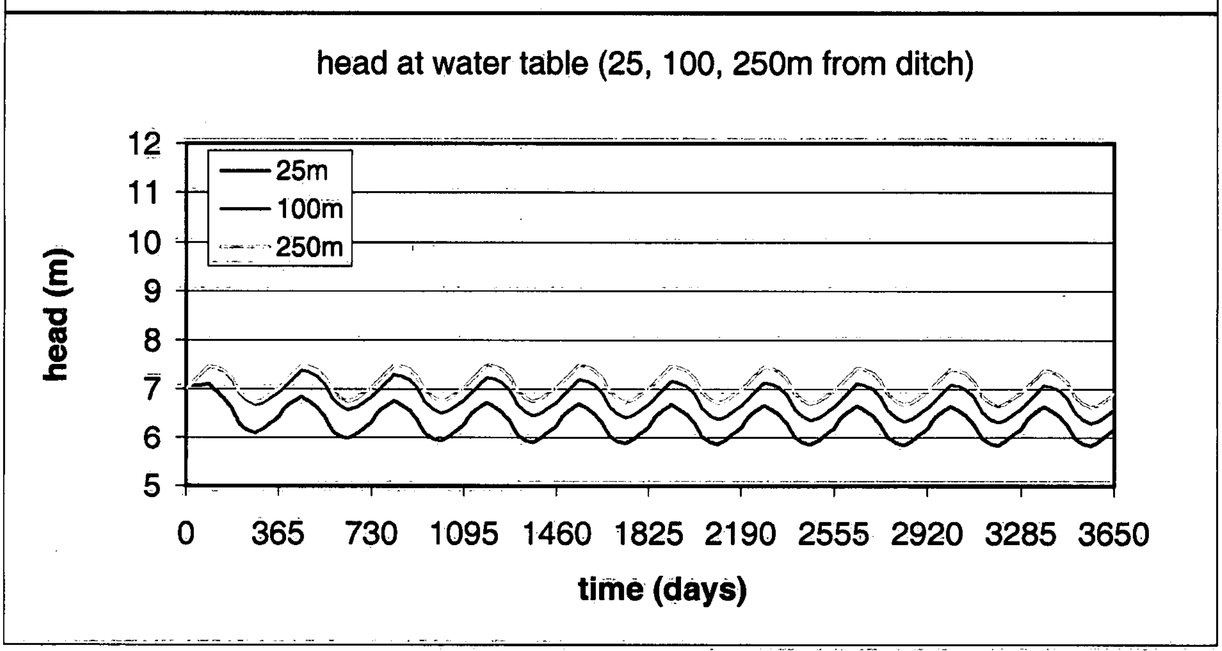
head at water table (25, 100, 250m from ditch)
head (m)
time (days)
25m
100m
250m



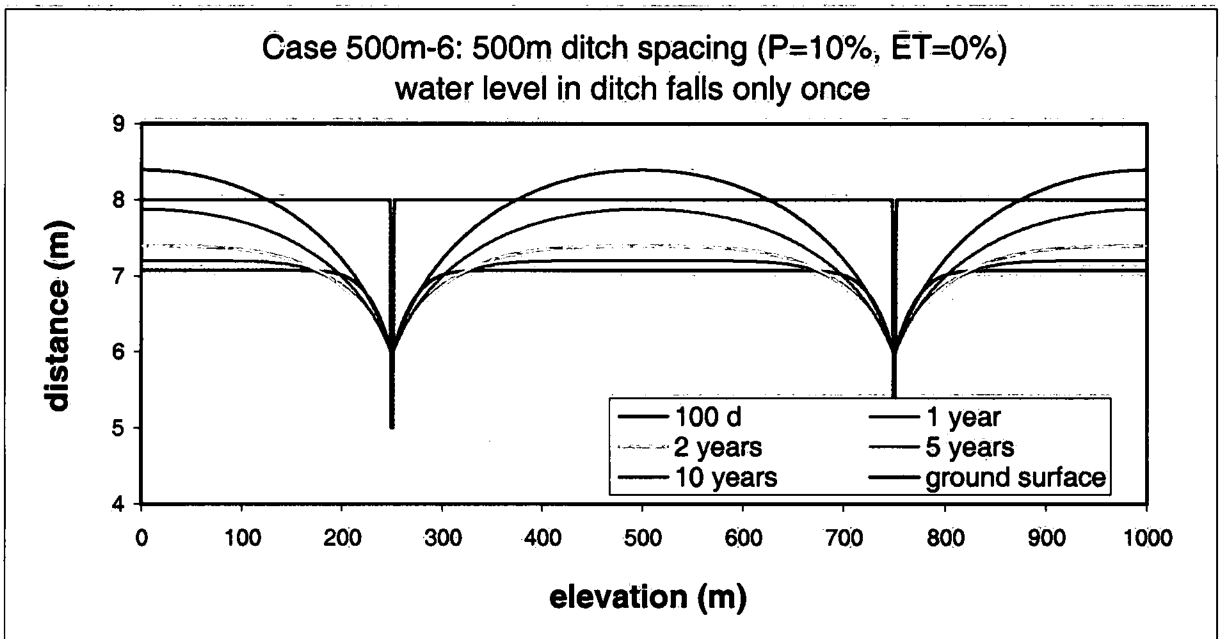
Case 500m-4: 500m ditch spacing (P=85%, ET=100%)
water level in ditch rises/falls annually
distance (m)
elevation (m)
100 d
1 year
2 years
5 years
10 years
ground surface
465 d
830 d
0
100
200
300
400
500
600
700
800
900
1000
4
5
6
7
8
9
head at water table (25, 100, 250m from ditch)
head (m)
time (days)
25m
100m
250m
0
365
730
1095
1460
1825
2190
2555
2920
3285
3650
5
6
7
8
9
10
11
12



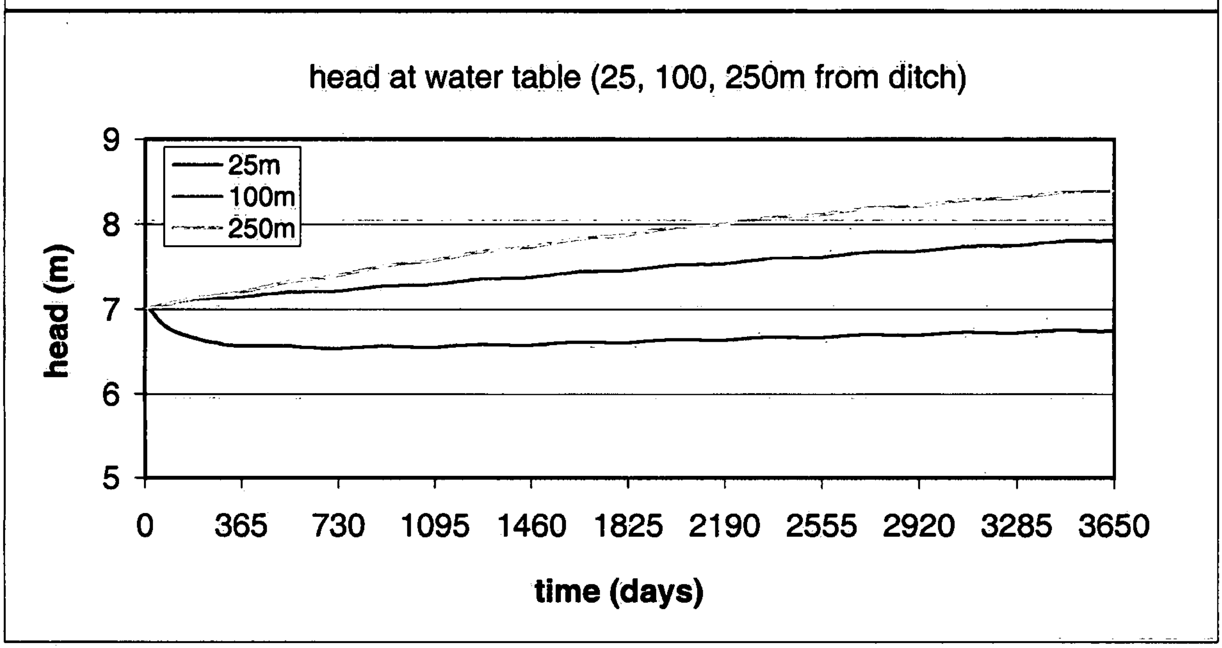
Case 500m-5: 500m ditch spacing (P=75%, ET=100%)
water level in ditch rises/falls annually
distance (m)
elevation (m)
100 d
1 year
2 years
5 years
10 years
ground surface
465 d
830 d
0
100
200
300
400
500
600
700
800
900
1000
4
5
6
7
8
9



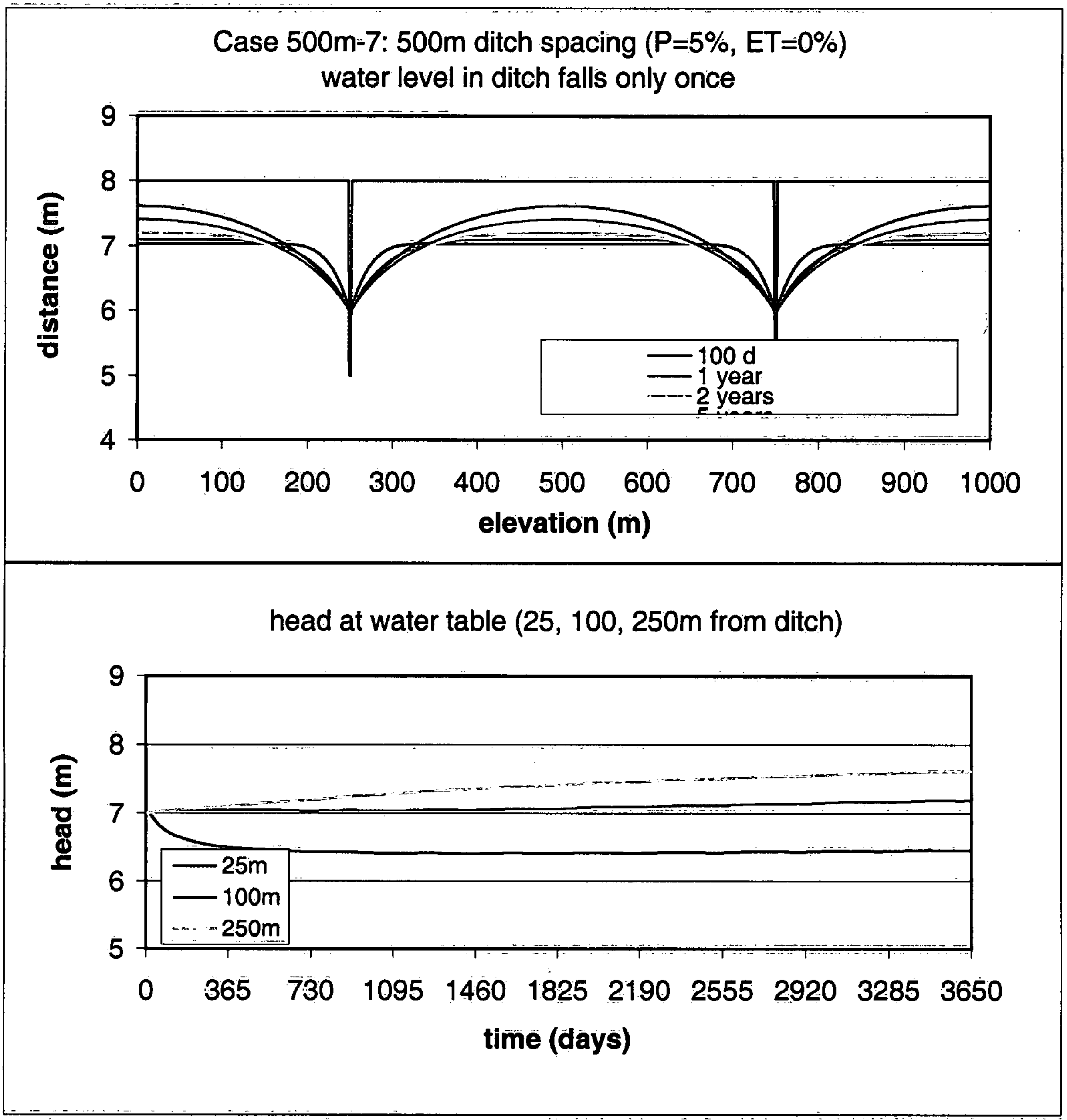
head at water table (25, 100, 250m from ditch)
head (m)
time (days)
25m
100m
250m
0
365
730
1095
1460
1825
2190
2555
2920
3285
3650
5
6
7
8
9
10
11
12



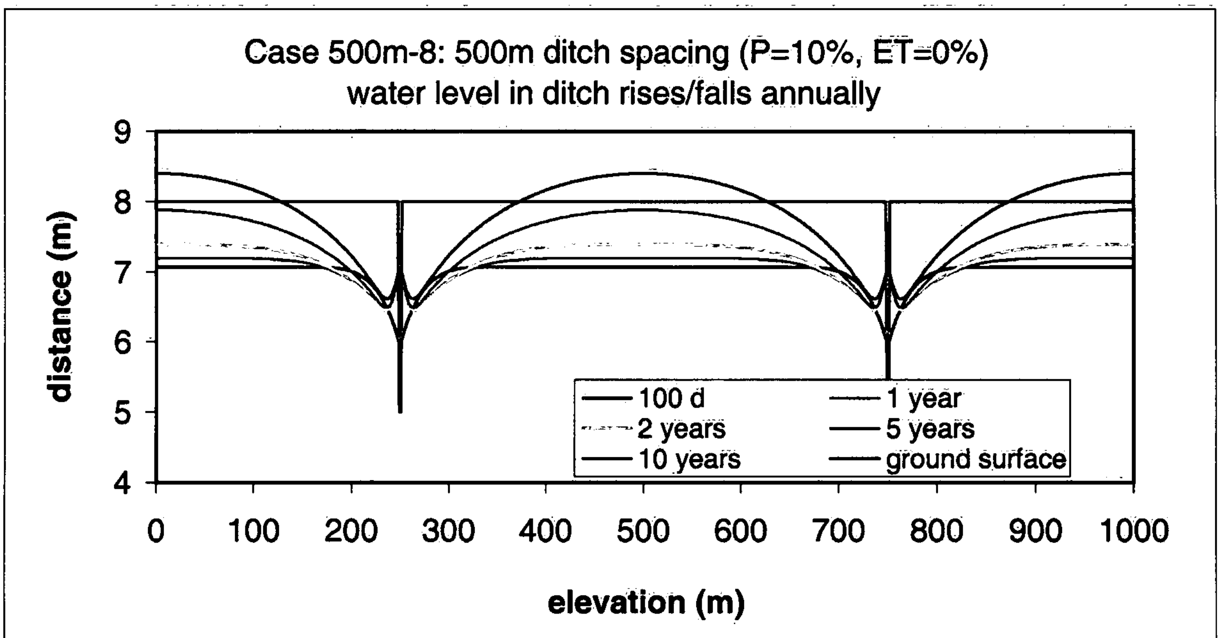
Case 500m-6: 500m ditch spacing (P=10%, ET=0%)
water level in ditch falls only once
distance (m)
elevation (m)
100 d
1 year
2 years
5 years
10 years
ground surface
9
8
7
6
5
4
0
100
200
300
400
500
600
700
800
900
1000



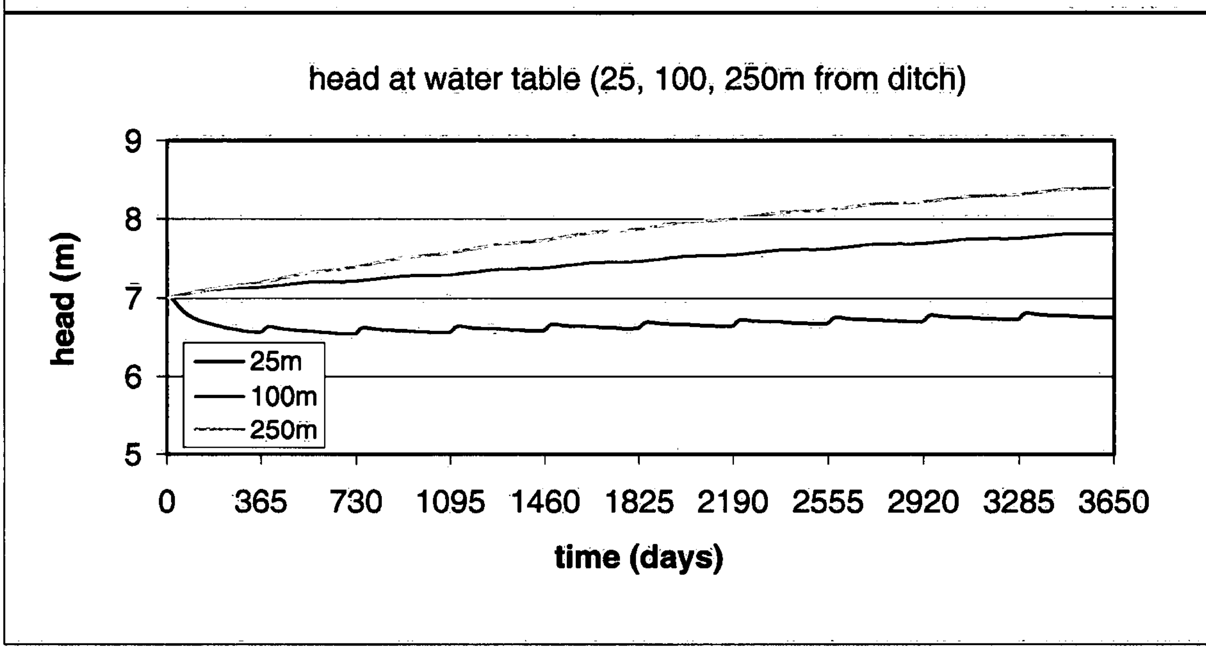
head at water table (25, 100, 250m from ditch)
25m
100m
250m
head (m)
time (days)
9
8
7
6
5
0
365
730
1095
1460
1825
2190
2555
2920
3285
3650



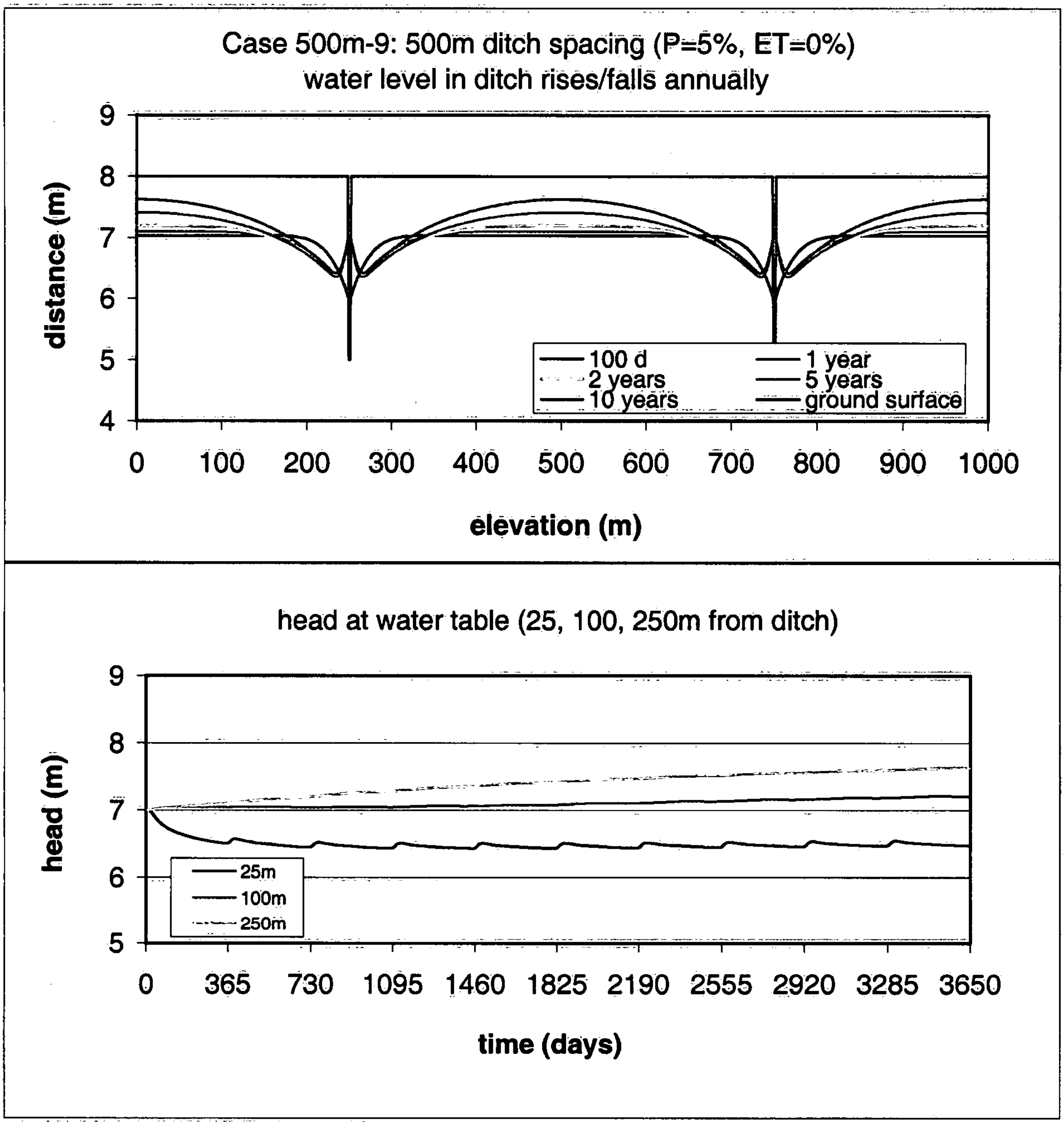
Case 500m-7: 500m ditch spacing (P=5%, ET=0%)
water level in ditch falls only once
distance (m)
elevation (m)
100 d
1 year
2 years
head at water table (25, 100, 250m from ditch)
head (m)
time (days)
25m
100m
250m



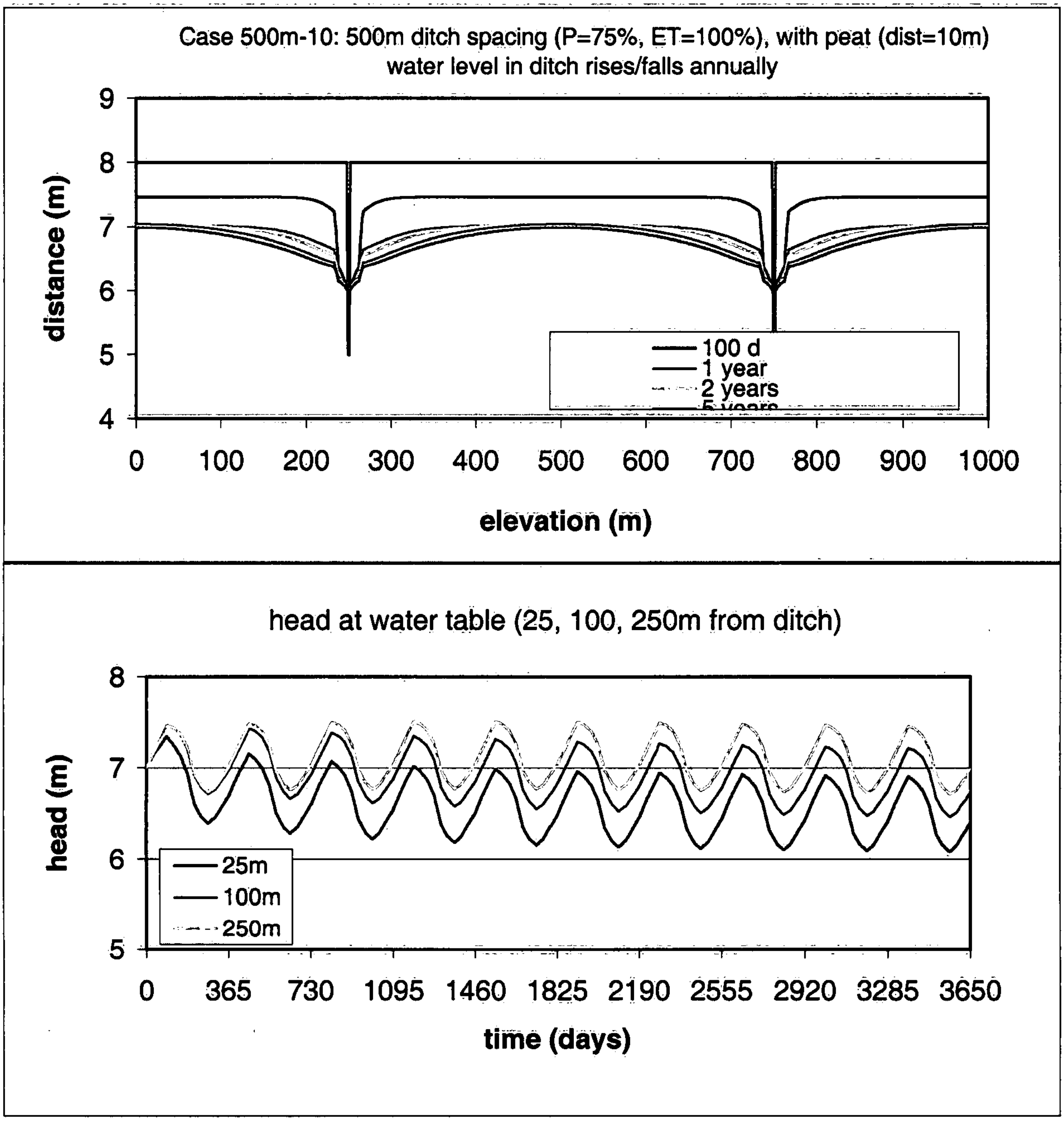
Case 500m-8: 500m ditch spacing (P=10%, ET=0%)
water level in ditch rises/falls annually
distance (m)
9
8
7
6
5
4
0
100
200
300
400
500
600
700
800
900
1000
elevation (m)
100 d
1 year
2 years
5 years
10 years
ground surface



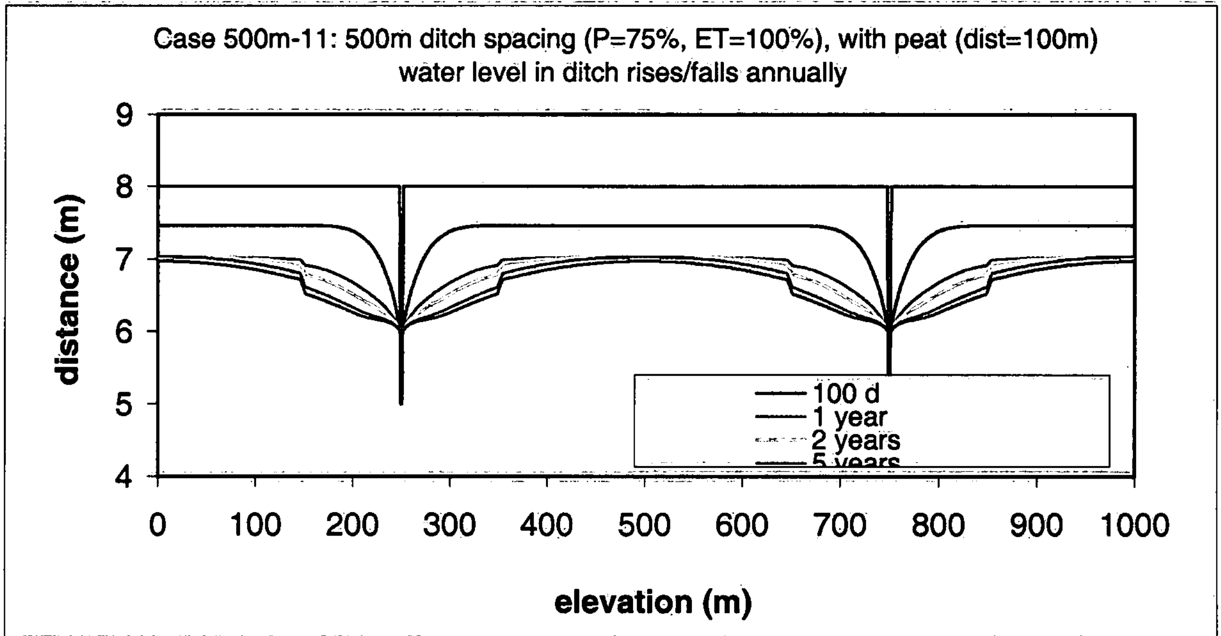
head at water table (25, 100, 250m from ditch)
head (m)
9
8
7
6
5
0
365
730
1095
1460
1825
2190
2555
2920
3285
3650
time (days)
25m
100m
250m



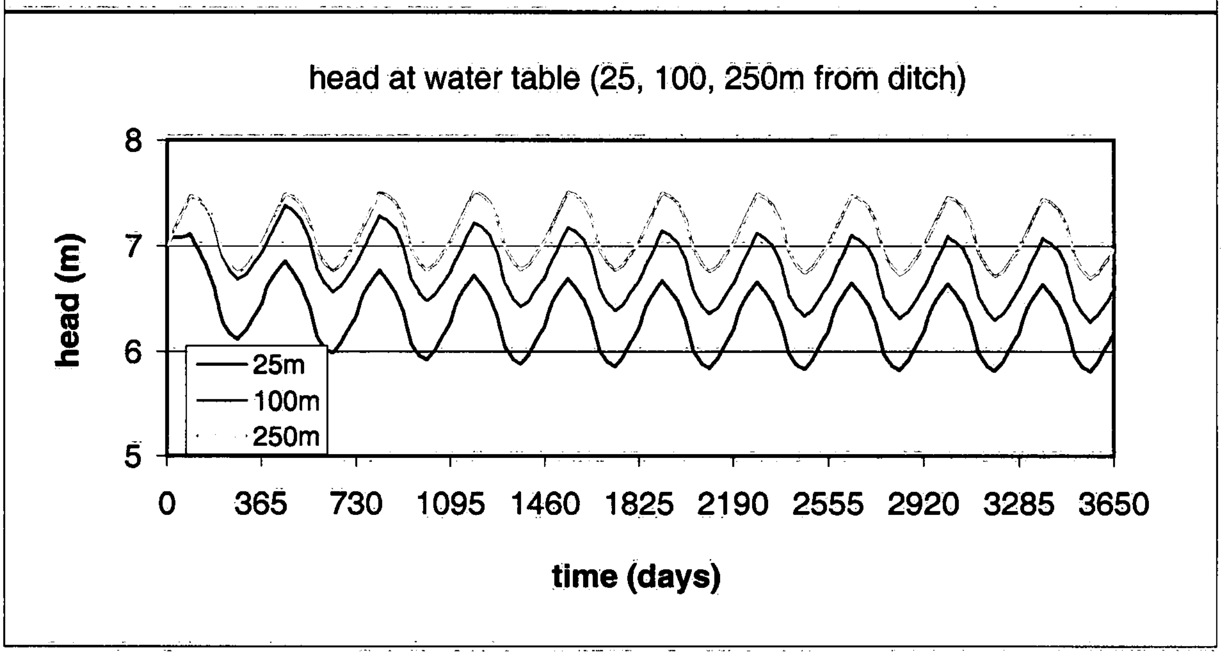
Case 500m-9: 500m ditch spacing (P=5%, ET=0%)
water level in ditch rises/falls annually
distance (m)
elevation (m)
100 d
1 year
2 years
5 years
10 years
ground surface
0
100
200
300
400
500
600
700
800
900
1000
4
5
6
7
8
9
head at water table (25, 100, 250m from ditch)
head (m)
time (days)
25m
100m
250m
0
365
730
1095
1460
1825
2190
2555
2920
3285
3650



Case 500m-10: 500m ditch spacing (P=75%, ET=100%), with peat (dist=10m)
water level in ditch rises/falls annually
distance (m)
elevation (m)
100 d
1 year
2 years
9
8
7
6
5
4
0
100
200
300
400
500
600
700
800
900
1000
head at water table (25, 100, 250m from ditch)
head (m)
time (days)
25m
100m
250m
8
7
6
5
0
365
730
1095
1460
1825
2190
2555
2920
3285
3650



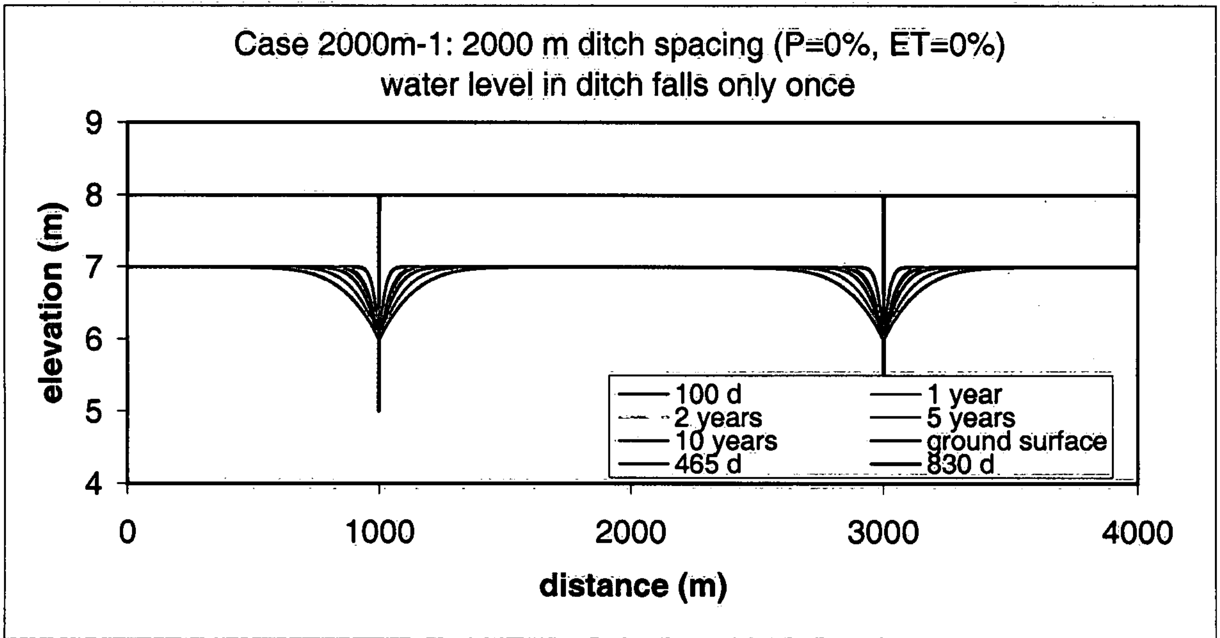
Case 500m-11: 500m ditch spacing (P=75%, ET=100%), with peat (dist=100m)
water level in ditch rises/falls annually
distance (m)
elevation (m)
100 d
1 year
2 years
5 years
9
8
7
6
5
4
0
100
200
300
400
500
600
700
800
900
1000



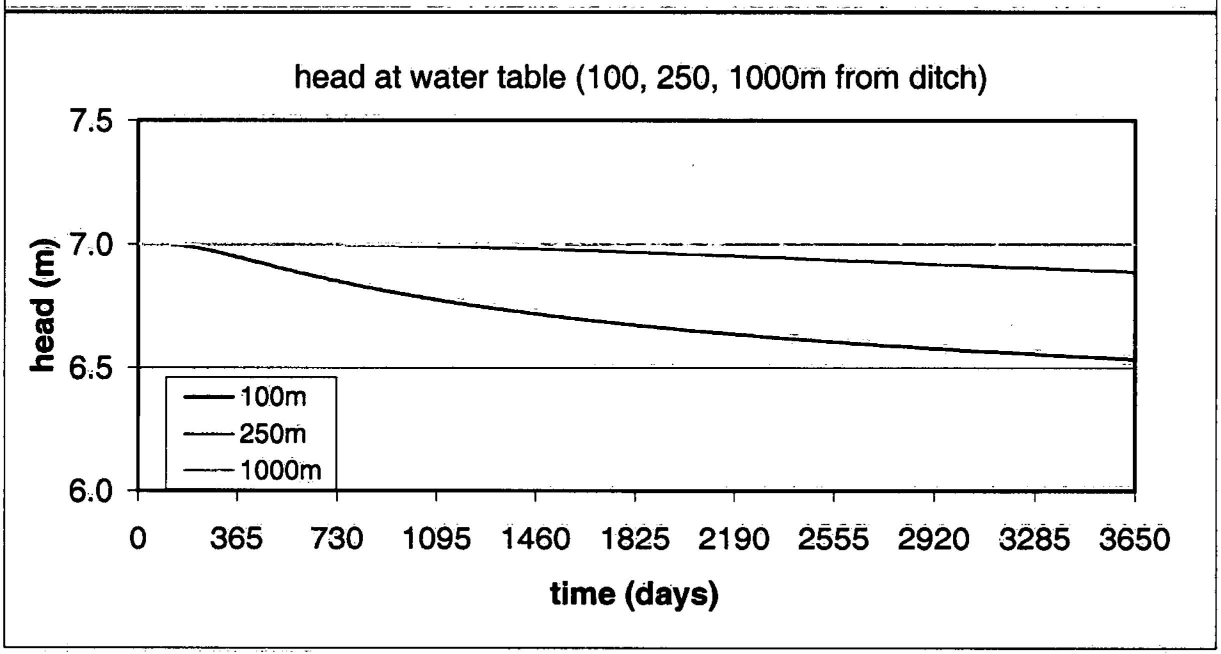
head at water table (25, 100, 250m from ditch)
head (m)
time (days)
25m
100m
250m
8
7
6
5
0
365
730
1095
1460
1825
2190
2555
2920
3285
3650

Appendix 4:

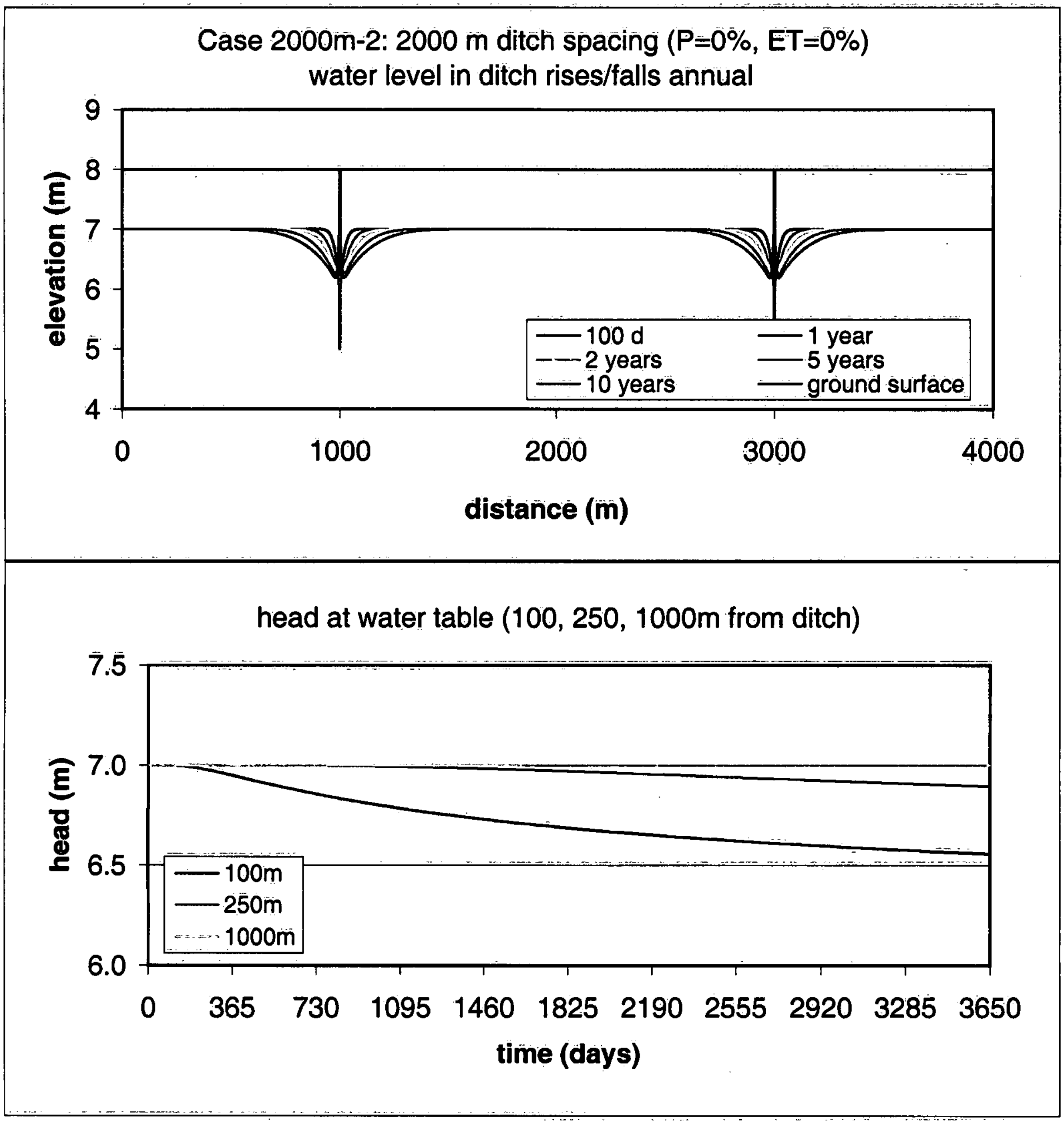
Impact of Drainage Ditches with a 2000m Spacing on the Water Table



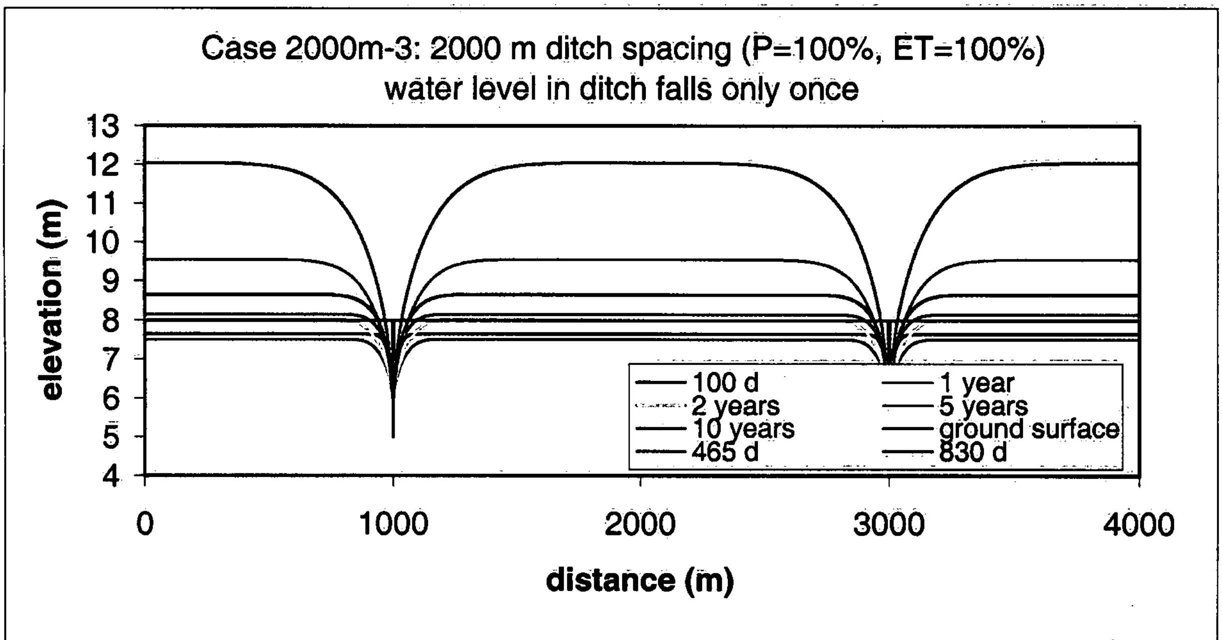
Case 2000m-1: 2000 m ditch spacing (P=0%, ET=0%)
water level in ditch falls only once
elevation (m)
9
8
7
6
5
4
0
1000
2000
3000
4000
distance (m)
100 d
1 year
2 years
5 years
10 years
ground surface
465 d
830 d

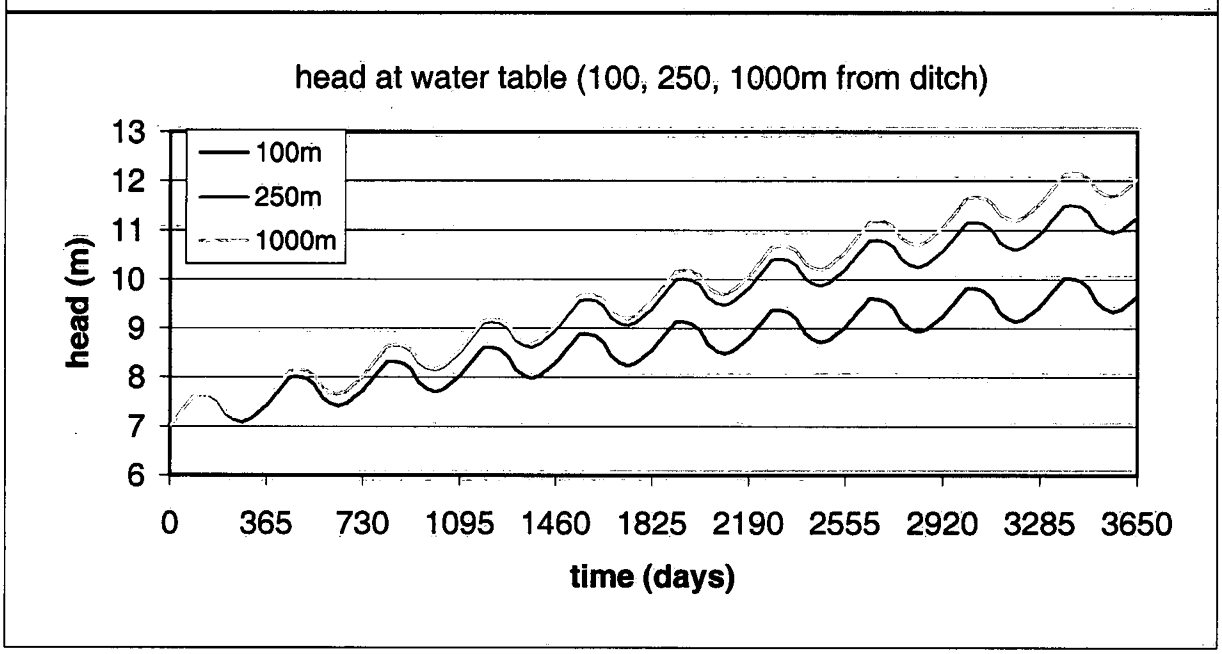


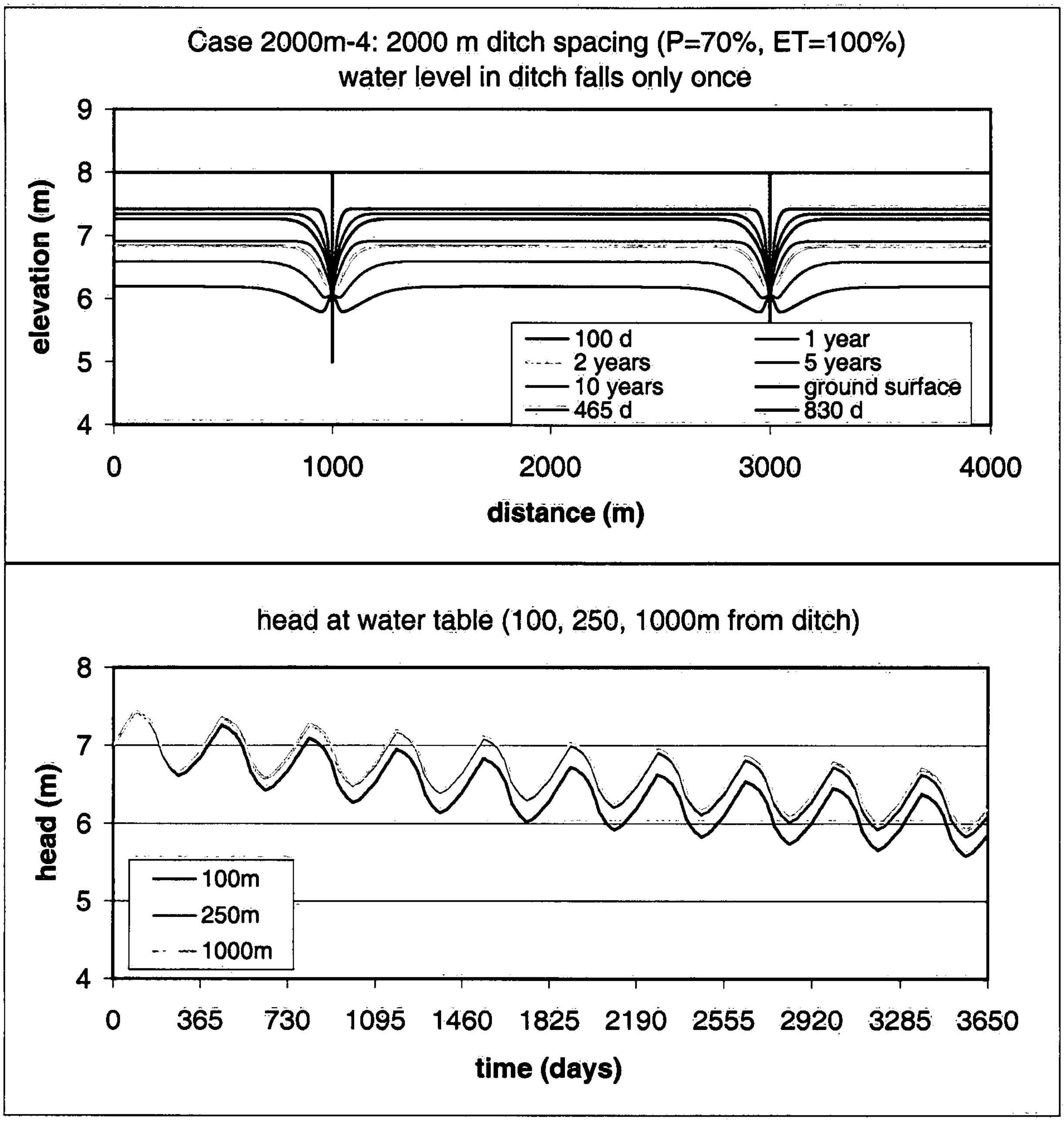
head at water table (100, 250, 1000m from ditch)
head (m)
7.5
7.0
6.5
6.0
0
365
730
1095
1460
1825
2190
2555
2920
3285
3650
time (days)
100m
250m
1000m



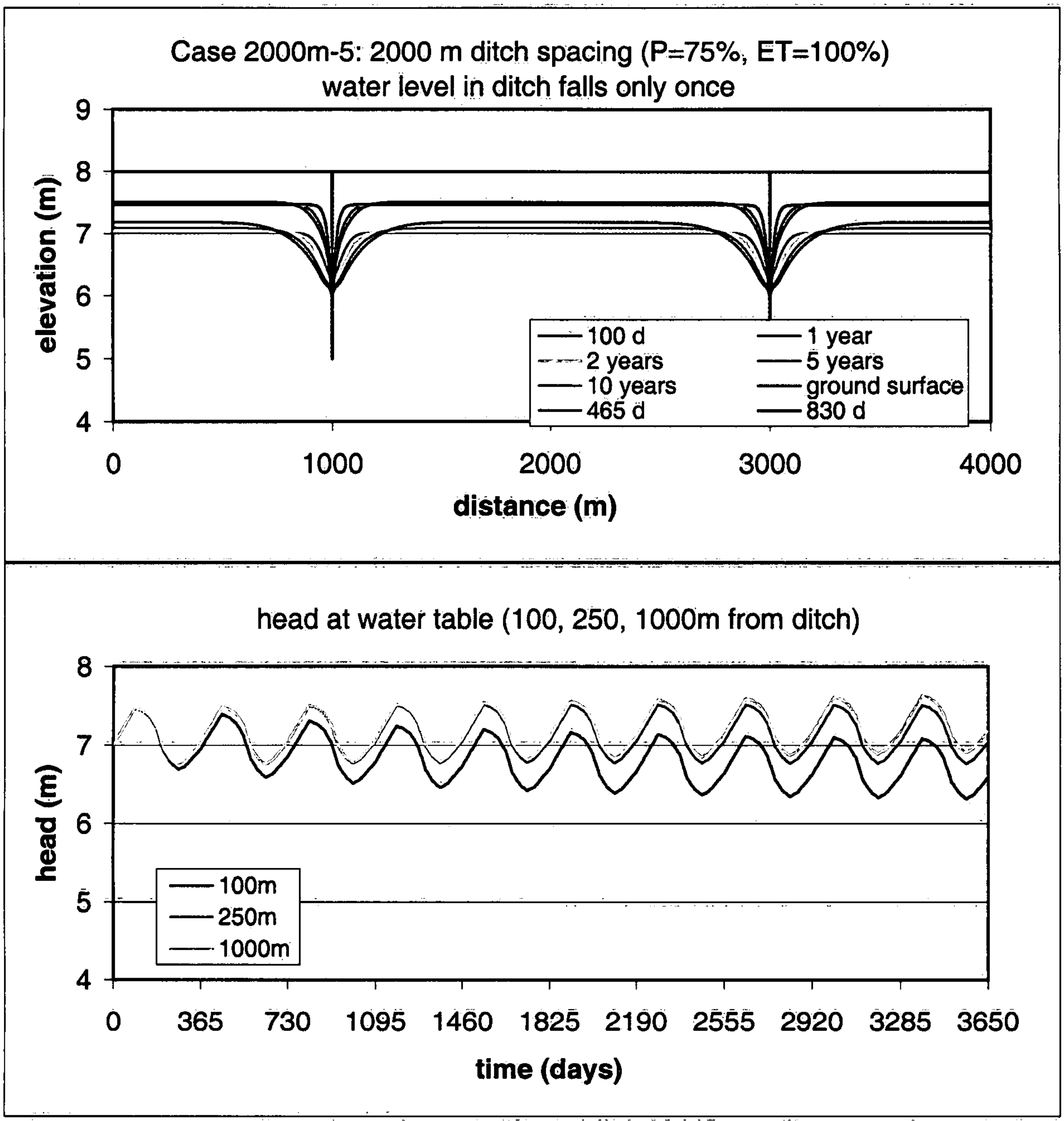
Case 2000m-2: 2000 m ditch spacing (P=0%, ET=0%)
water level in ditch rises/falls annual
elevation (m)
9
8
7
6
5
4
0
1000
2000
3000
4000
distance (m)
100 d
1 year
2 years
5 years
10 years
ground surface
head at water table (100, 250, 1000m from ditch)
head (m)
7.5
7.0
6.5
6.0
100m
250m
1000m
0
365
730
1095
1460
1825
2190
2555
2920
3285
3650
time (days)

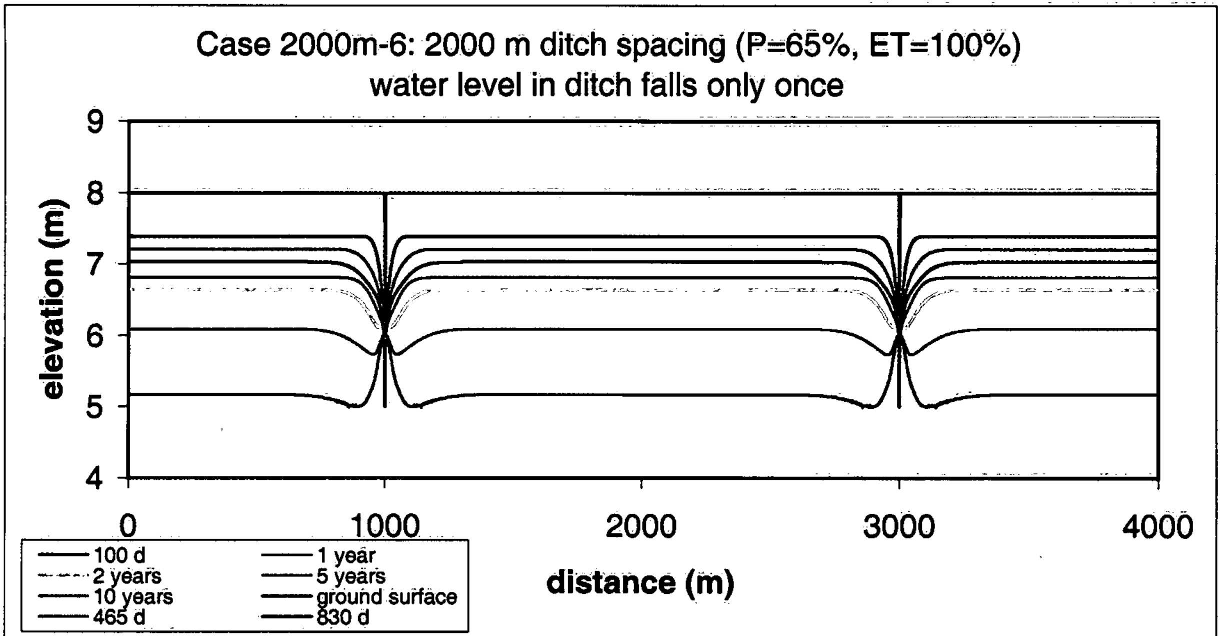

Case 2000m-3: 2000 m ditch spacing (P=100%, ET=100%)
water level in ditch falls only once
elevation (m)
13
12
11
10
9
8
7
6
5
4
0
1000
2000
3000
4000
distance (m)
100 d
1 year
2 years
5 years
10 years
ground surface
465 d
830 d


head at water table (100, 250, 1000m from ditch)
head (m)
13
12
11
10
9
8
7
6
0
365
730
1095
1460
1825
2190
2555
2920
3285
3650
time (days)
100m
250m
1000m

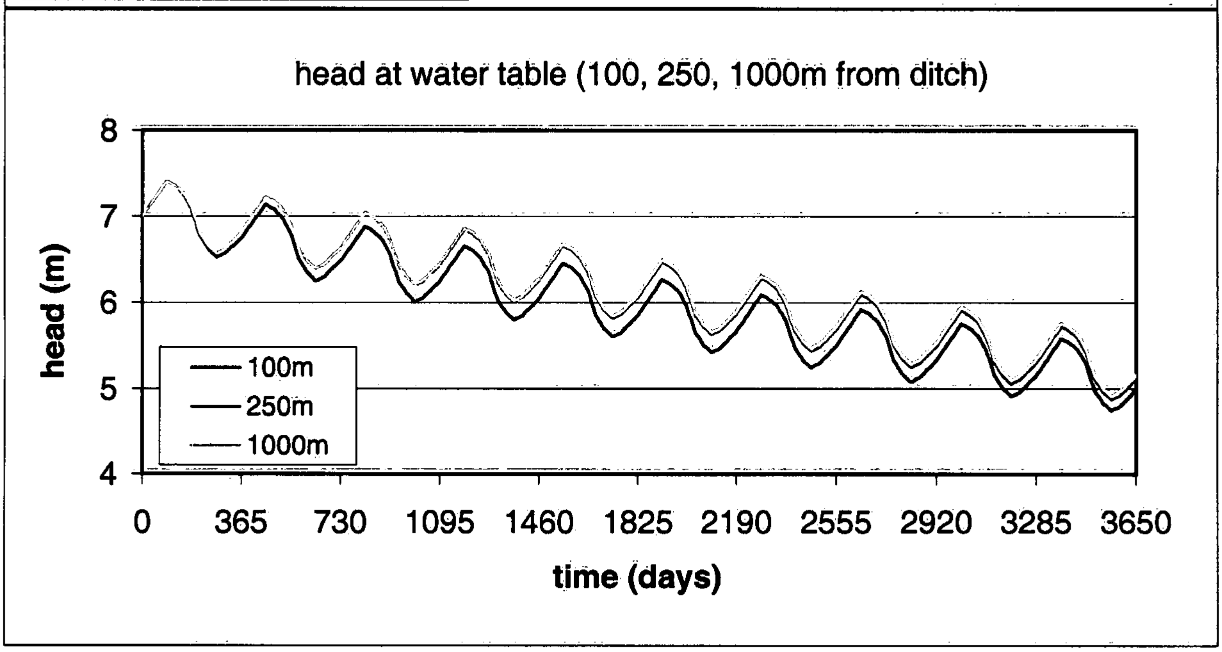


Case 2000m-4: 2000 m ditch spacing (P=70%, ET=100%)
water level in ditch falls only once
elevation (m)
distance (m)
0
1000
2000
3000
4000
4
5
6
7
8
9
100 d
1 year
2 years
5 years
10 years
ground surface
465 d
830 d
head at water table (100, 250, 1000m from ditch)
head (m)
time (days)
0
365
730
1095
1460
1825
2190
2555
2920
3285
3650
100m
250m
1000m

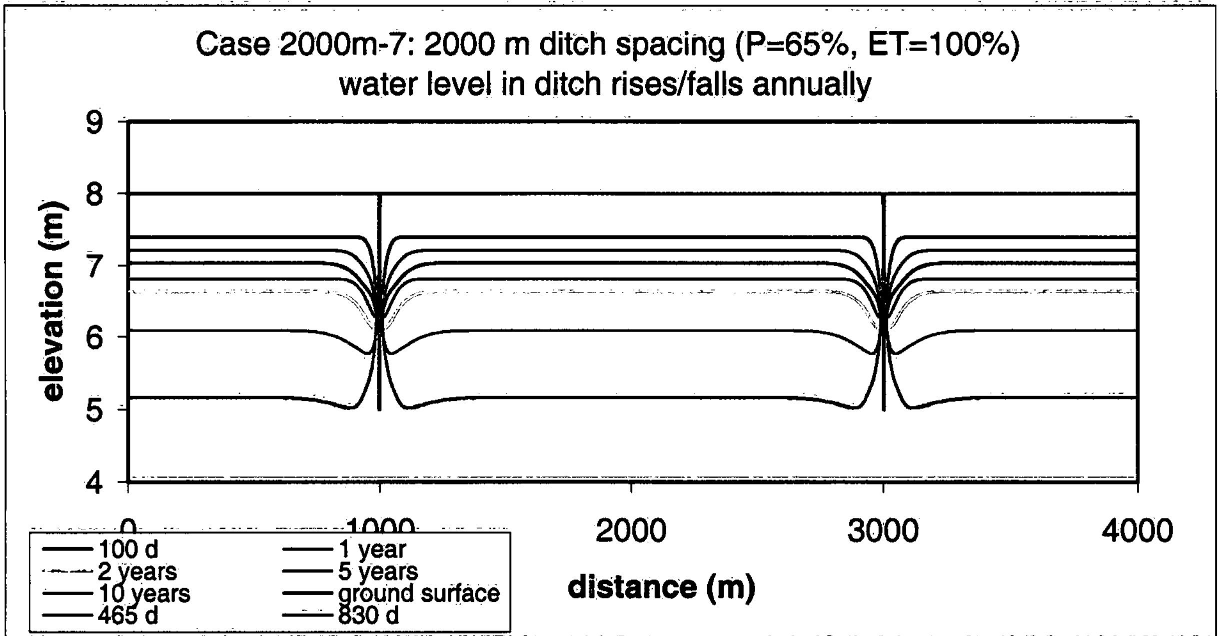

Case 2000m-5: 2000 m ditch spacing (P=75%, ET=100%)
water level in ditch falls only once
elevation (m)
distance (m)
100 d
1 year
2 years
5 years
10 years
ground surface
465 d
830 d
head at water table (100, 250, 1000m from ditch)
head (m)
time (days)
100m
250m
1000m

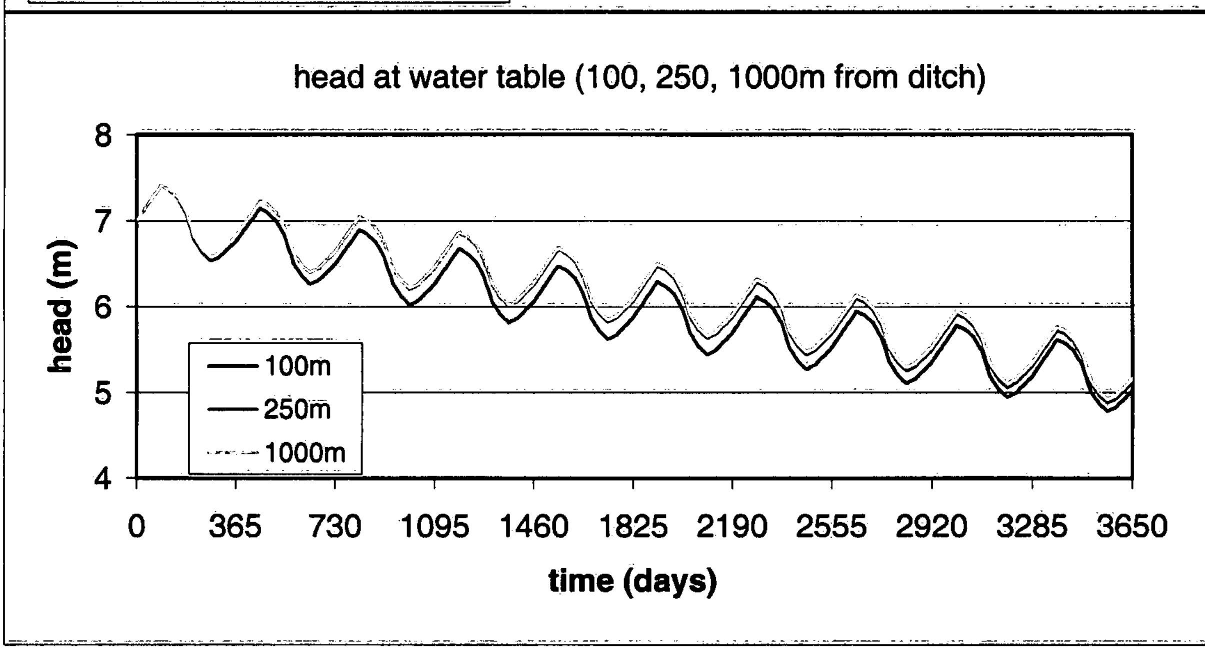


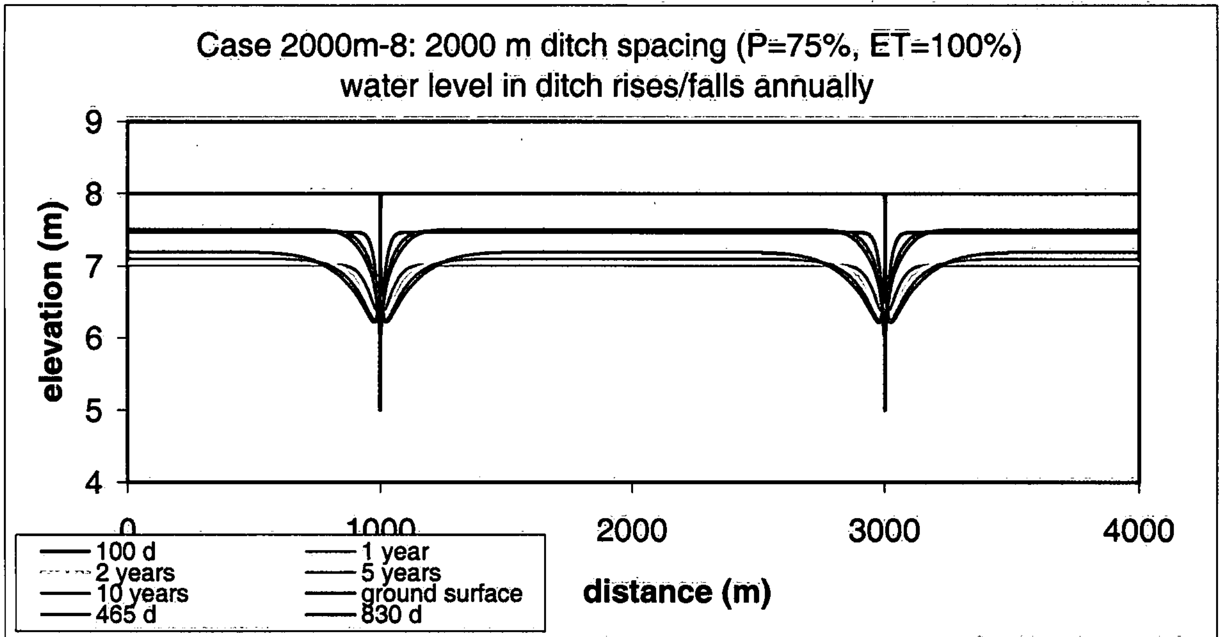
Case 2000m-6: 2000 m ditch spacing (P=65%, ET=100%)
water level in ditch falls only once
elevation (m)
distance (m)
100 d
1 year
2 years
5 years
10 years
ground surface
465 d
830 d

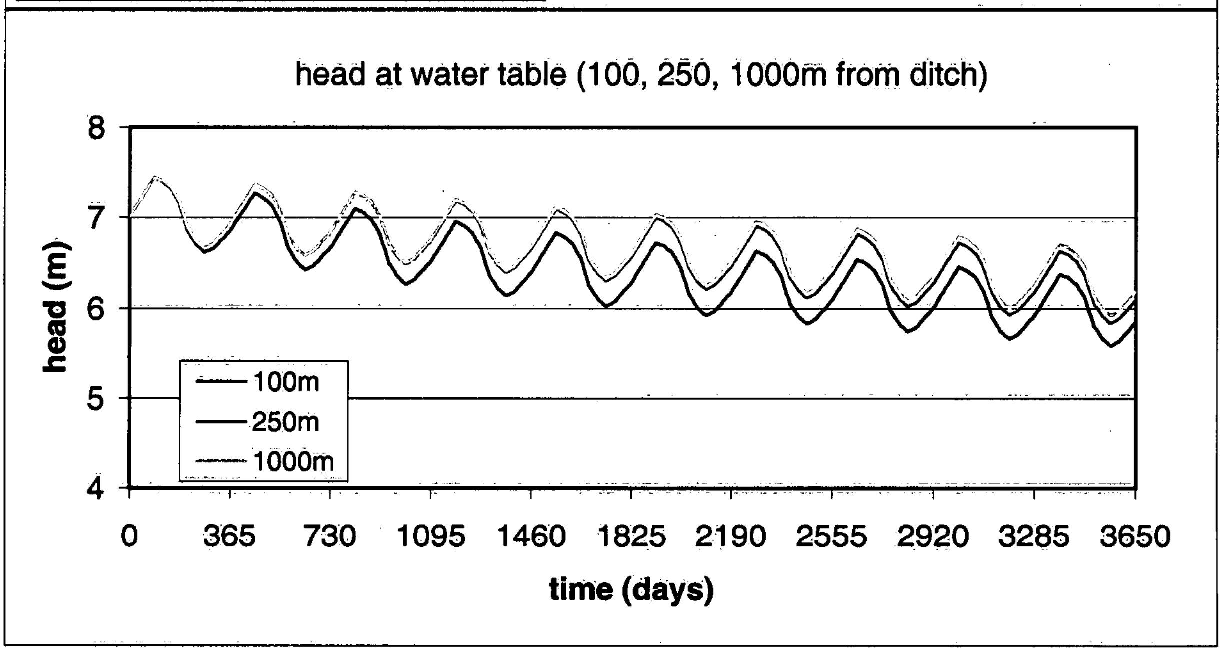


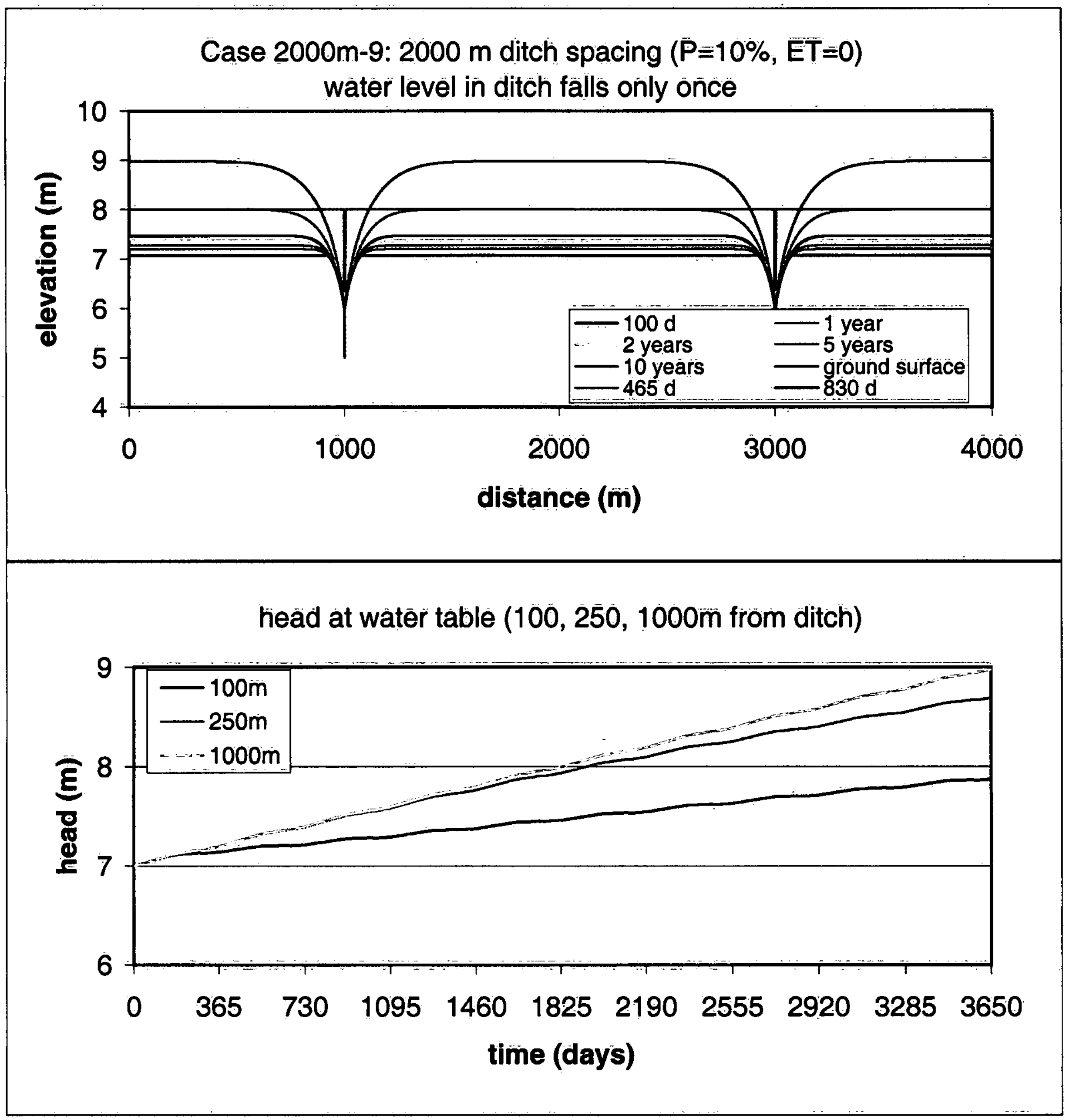
head at water table (100, 250, 1000m from ditch)
head (m)
time (days)
100m
250m
1000m

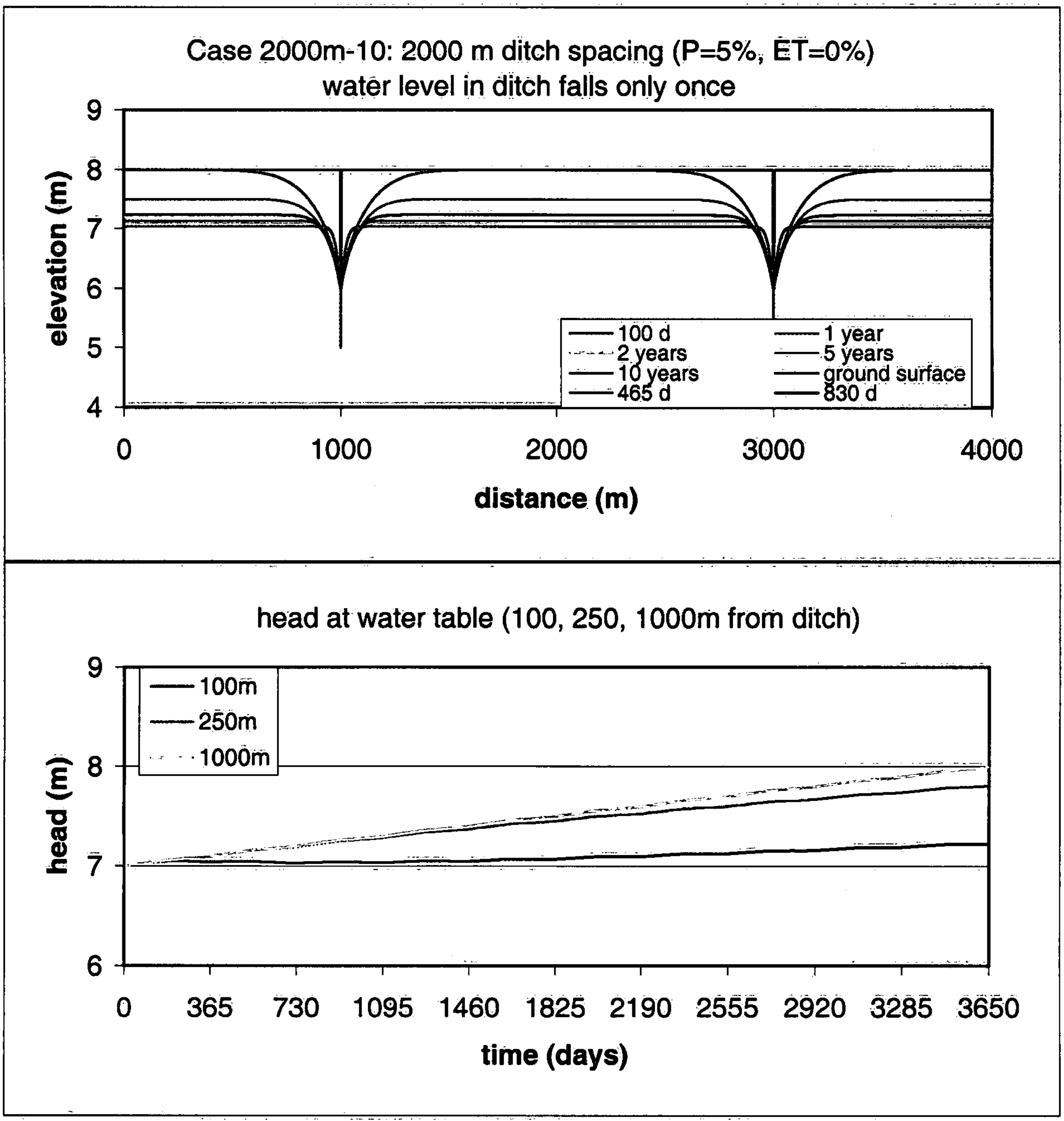

Case 2000m-7: 2000 m ditch spacing (P=65%, ET=100%)
water level in ditch rises/falls annually
elevation (m)
9
8
7
6
5
4
0
1000
2000
3000
4000
distance (m)
100 d
1 year
2 years
5 years
10 years
ground surface
465 d
830 d

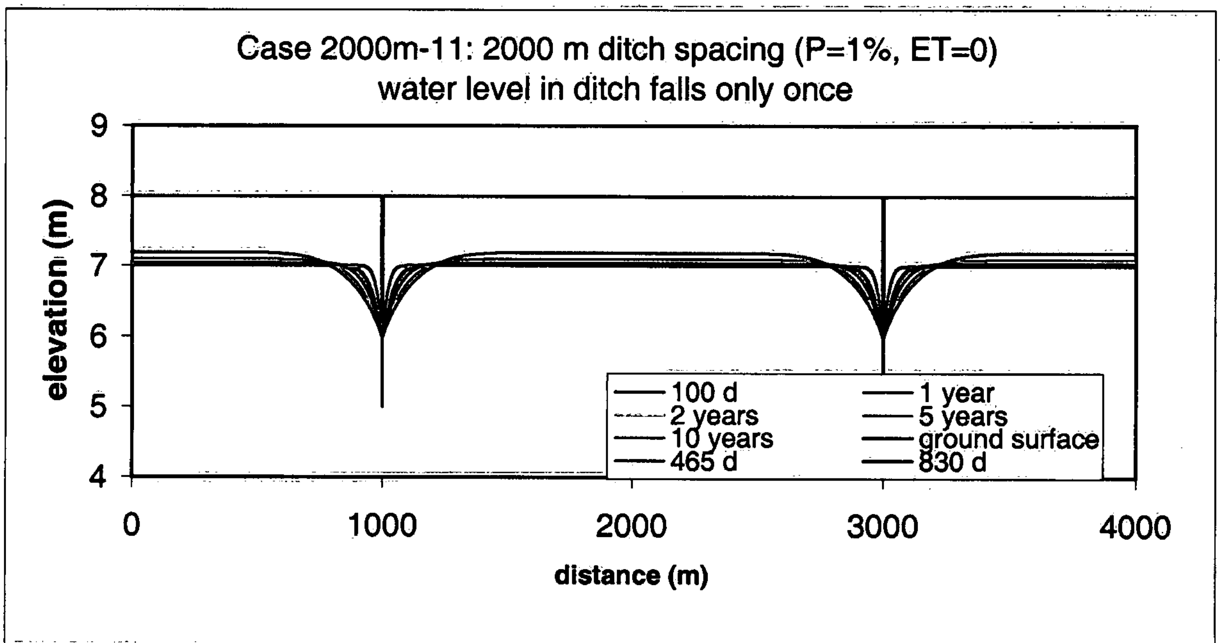

head at water table (100, 250, 1000m from ditch)
head (m)
8
7
6
5
4
0
365
730
1095
1460
1825
2190
2555
2920
3285
3650
time (days)
100m
250m
1000m


Case 2000m-8: 2000 m ditch spacing (P=75%, ET=100%)
water level in ditch rises/falls annually
elevation (m)
9
8
7
6
5
4
0
1000
2000
3000
4000
distance (m)
100 d
1 year
2 years
5 years
10 years
ground surface
465 d
830 d

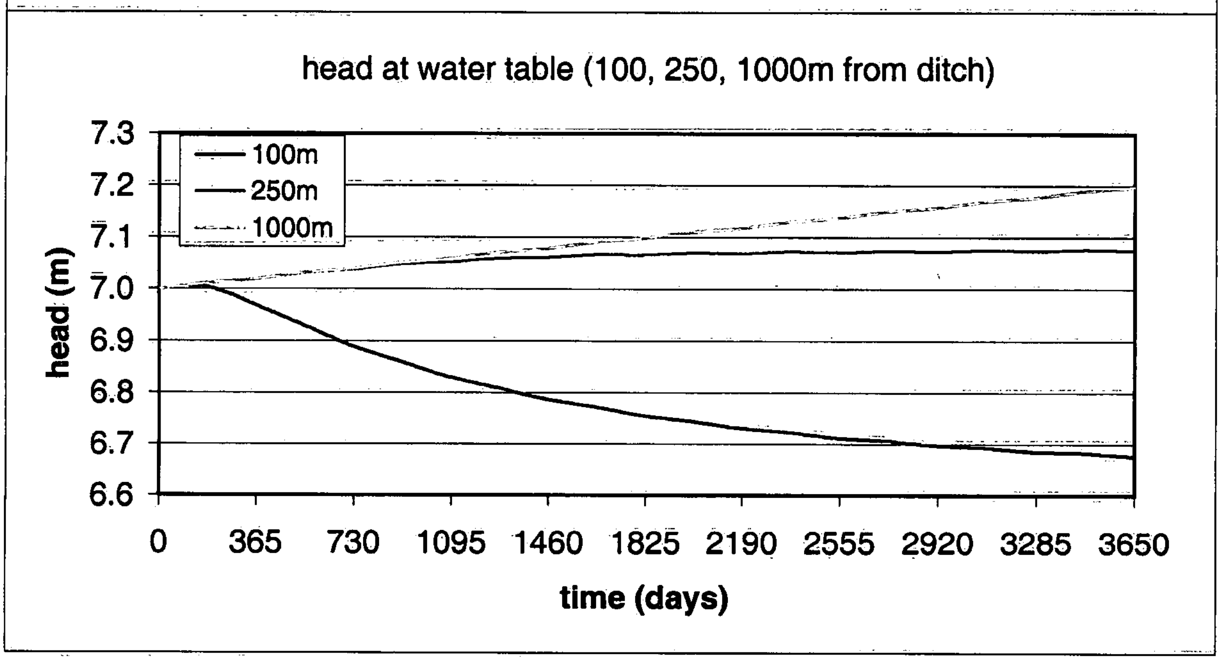

head at water table (100, 250, 1000m from ditch)
head (m)
8
7
6
5
4
0
365
730
1095
1460
1825
2190
2555
2920
3285
3650
time (days)
100m
250m
1000m


Case 2000m-9: 2000 m ditch spacing (P=10%, ET=0)
water level in ditch falls only once
elevation (m)
10
9
8
7
6
5
4
0
1000
2000
3000
4000
distance (m)
100 d
1 year
2 years
5 years
10 years
ground surface
465 d
830 d
head at water table (100, 250, 1000m from ditch)
head (m)
9
8
7
6
100m
250m
1000m
0
365
730
1095
1460
1825
2190
2555
2920
3285
3650
time (days)

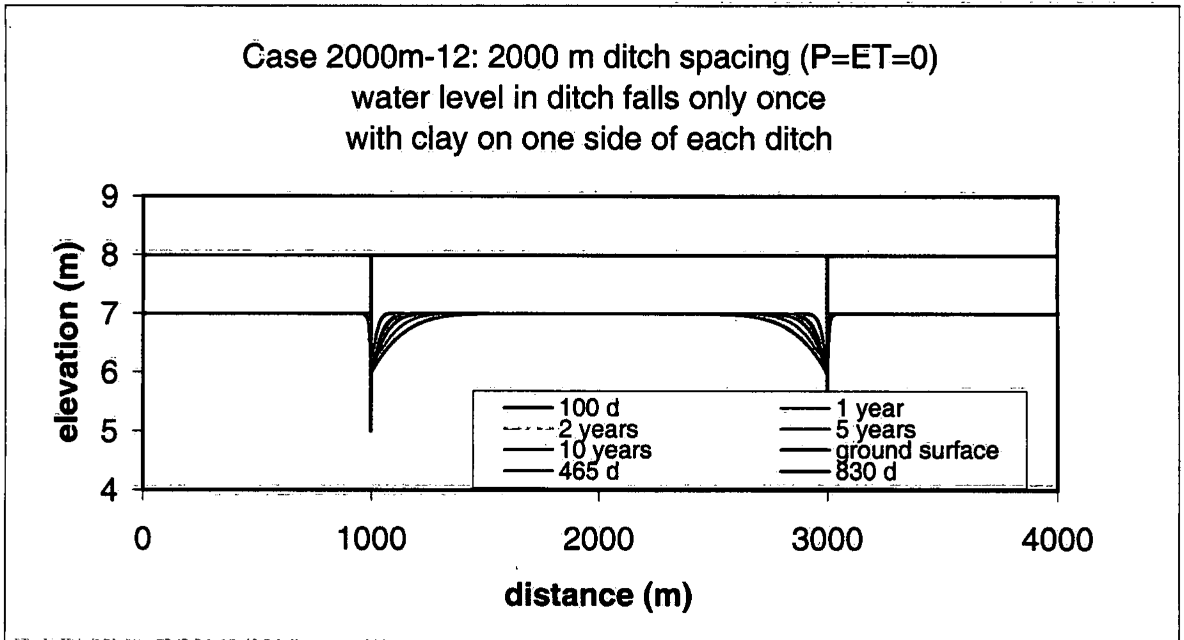

Case 2000m-10: 2000 m ditch spacing (P=5%, ET=0%)
water level in ditch falls only once
elevation (m)
distance (m)
0
1000
2000
3000
4000
9
8
7
6
5
4
100 d
1 year
2 years
5 years
10 years
ground surface
465 d
830 d
head at water table (100, 250, 1000m from ditch)
head (m)
time (days)
100m
250m
1000m
0
365
730
1095
1460
1825
2190
2555
2920
3285
3650

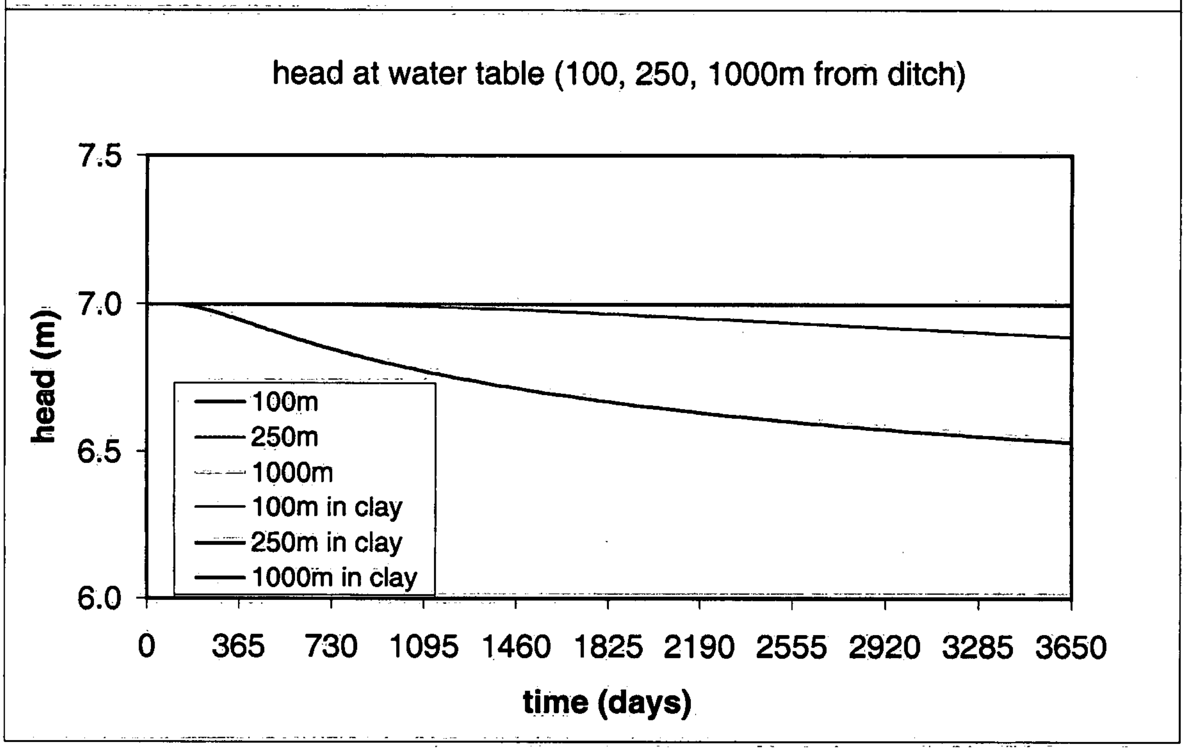


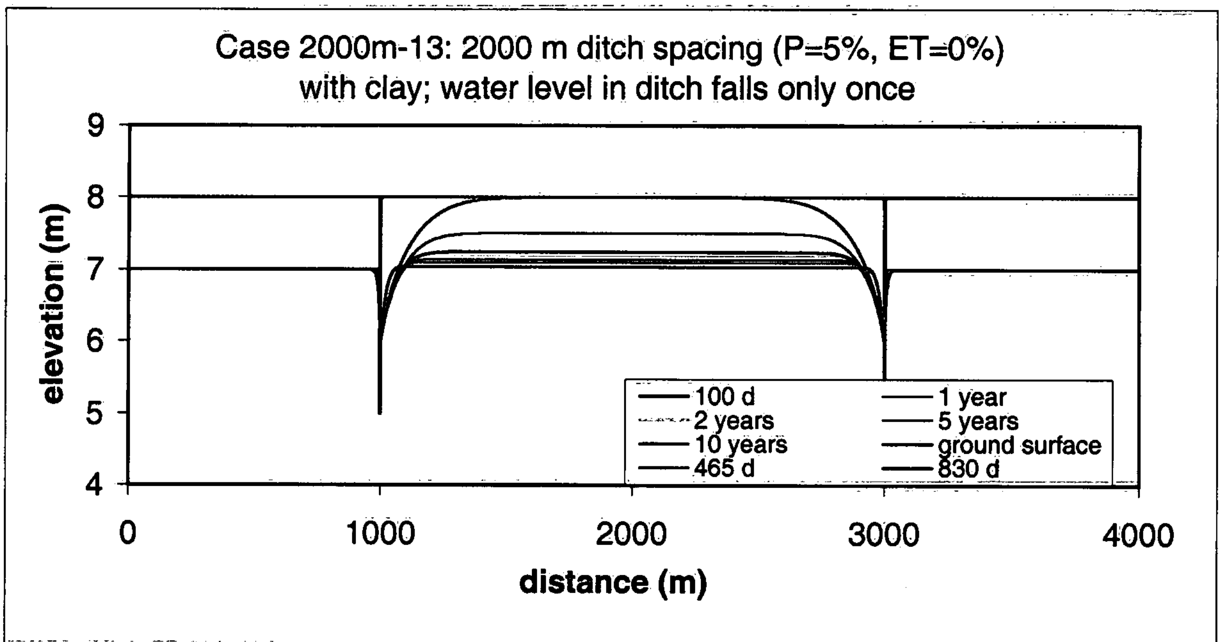
Case 2000m-11: 2000 m ditch spacing (P=1%, ET=0)
water level in ditch falls only once
elevation (m)
distance (m)
100 d
2 years
10 years
465 d
1 year
5 years
ground surface
830 d



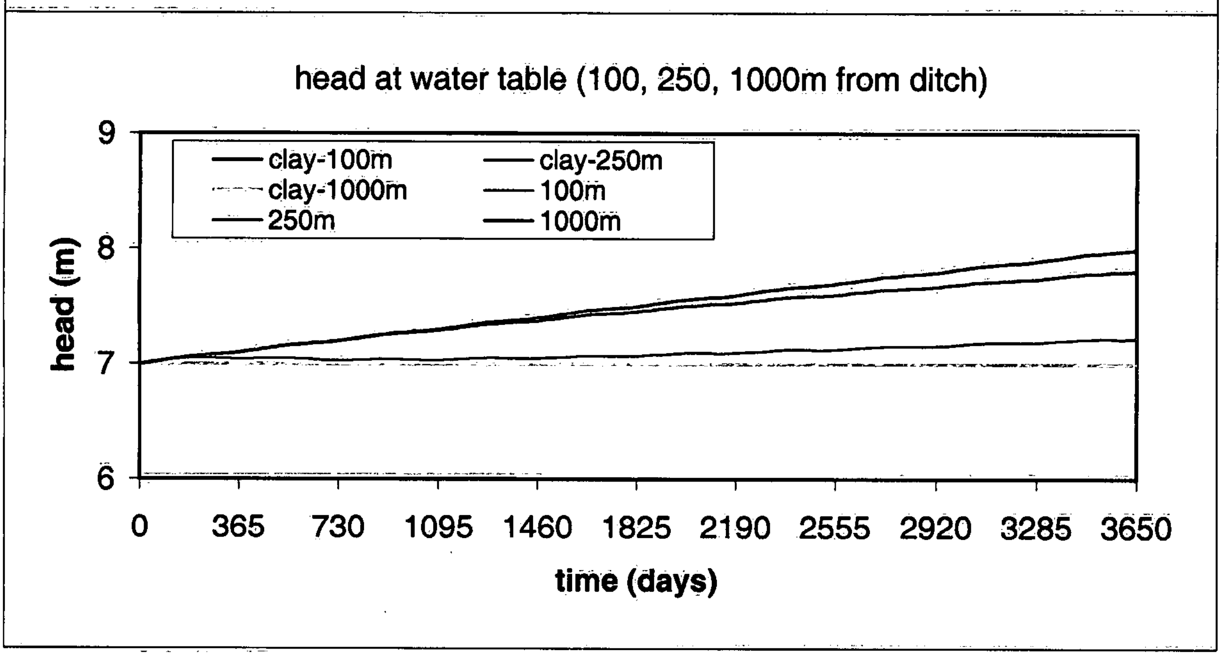
head at water table (100, 250, 1000m from ditch)
head (m)
time (days)
100m
250m
1000m


Case 2000m-12: 2000 m ditch spacing (P=ET=0)
water level in ditch falls only once
with clay on one side of each ditch
elevation (m)
distance (m)
100 d
1 year
2 years
5 years
10 years
ground surface
465 d
830 d
9
8
7
6
5
4
0
1000
2000
3000
4000

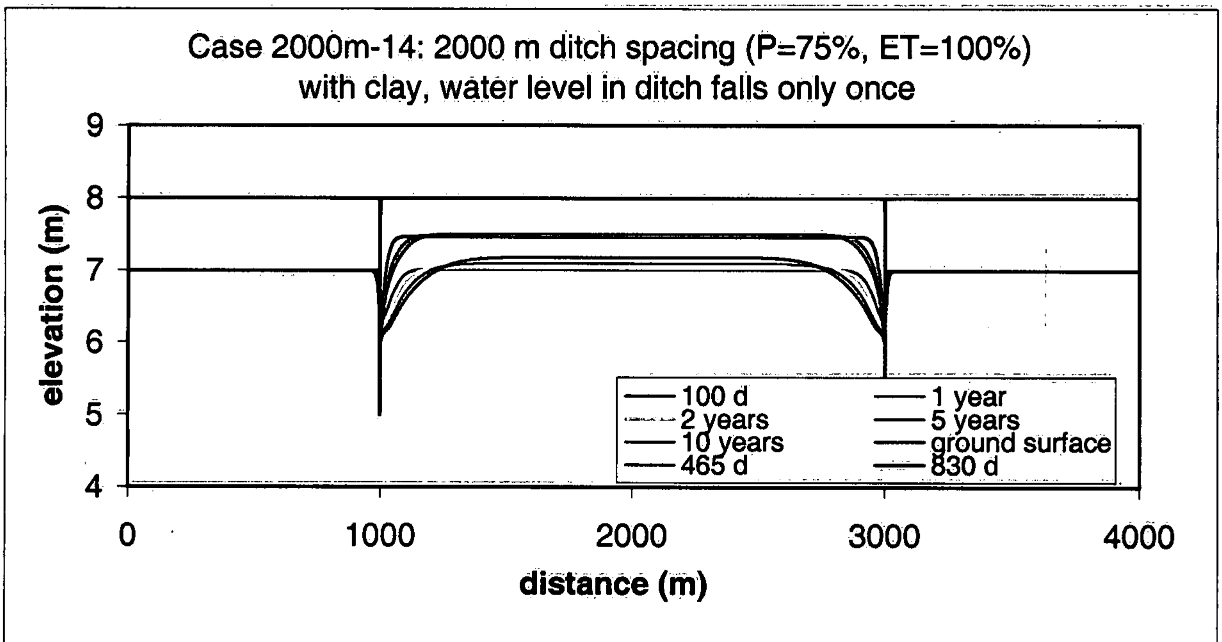

head at water table (100, 250, 1000m from ditch)
head (m)
time (days)
100m
250m
1000m
100m in clay
250m in clay
1000m in clay
7.5
7.0
6.5
6.0
0
365
730
1095
1460
1825
2190
2555
2920
3285
3650

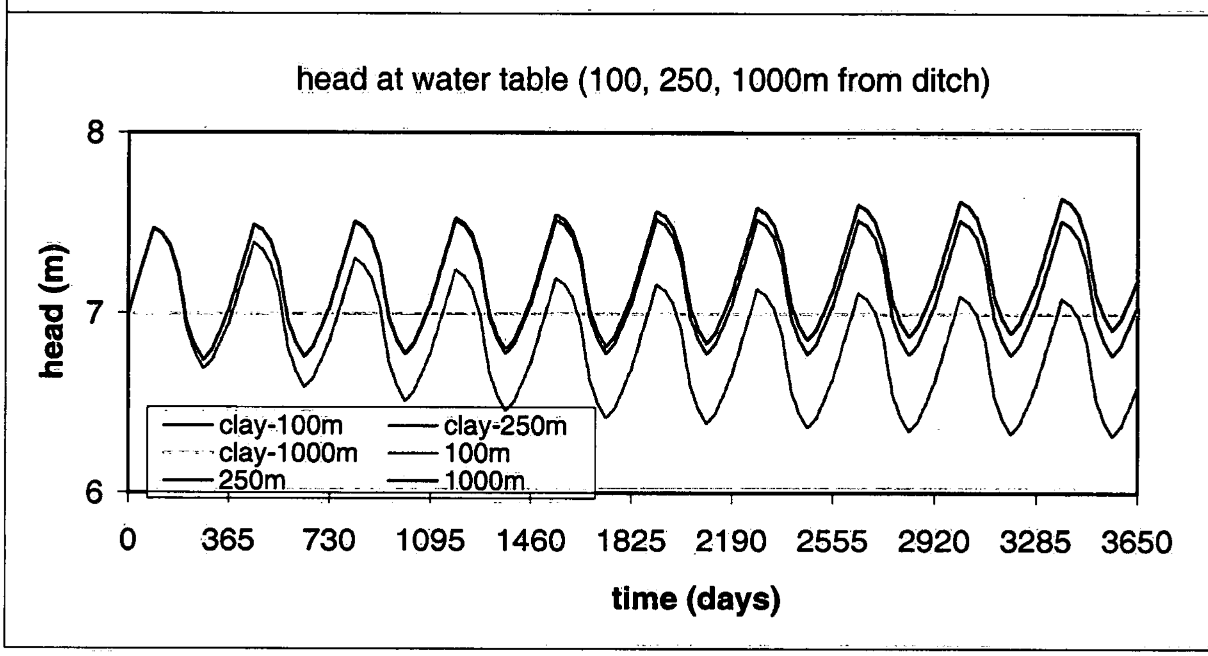


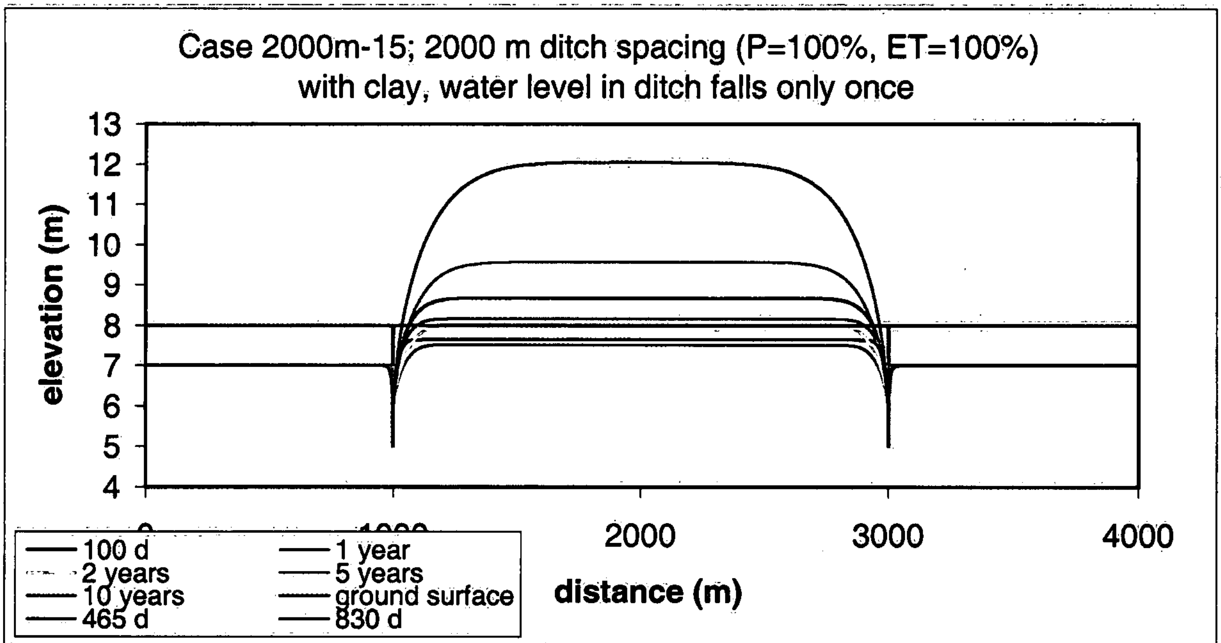
Case 2000m-13: 2000 m ditch spacing (P=5%, ET=0%)
with clay; water level in ditch falls only once
elevation (m)
9
8
7
6
5
4
0
1000
2000
3000
4000
distance (m)
100 d
1 year
2 years
5 years
10 years
ground surface
465 d
830 d



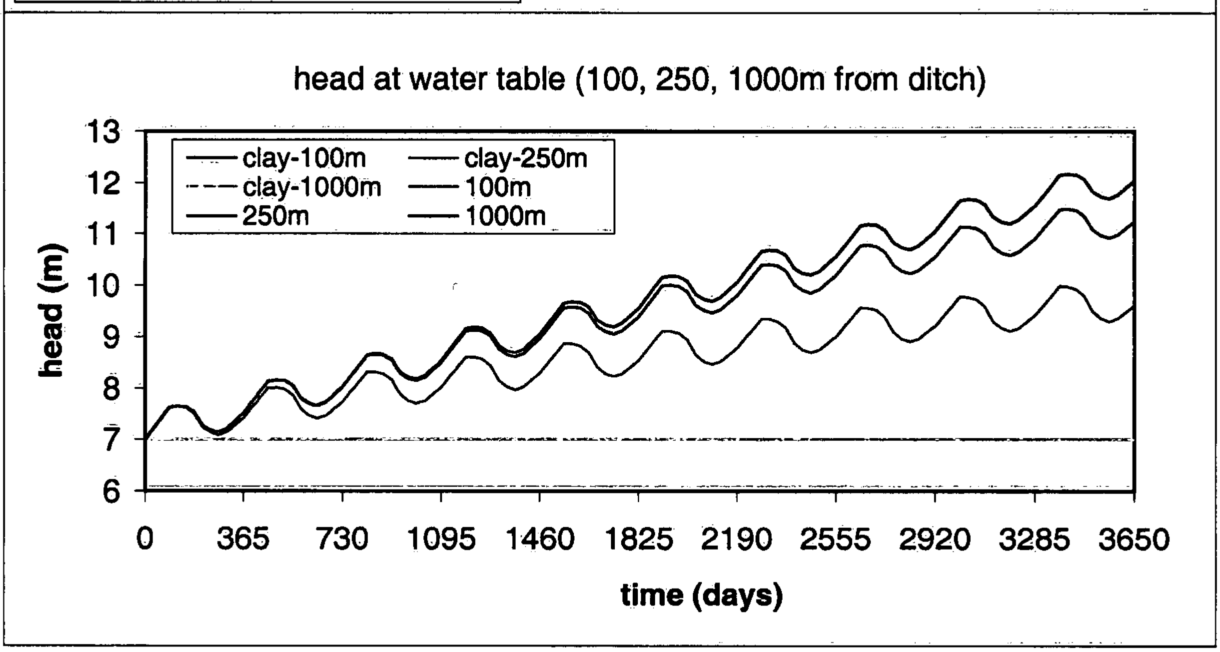
head at water table (100, 250, 1000m from ditch)
head (m)
9
8
7
6
clay-100m
clay-250m
clay-1000m
100m
250m
1000m
0
365
730
1095
1460
1825
2190
2555
2920
3285
3650
time (days)


Case 2000m-14: 2000 m ditch spacing (P=75%, ET=100%)
with clay, water level in ditch falls only once
elevation (m)
9
8
7
6
5
4
0
1000
2000
3000
4000
distance (m)
100 d
1 year
2 years
5 years
10 years
ground surface
465 d
830 d

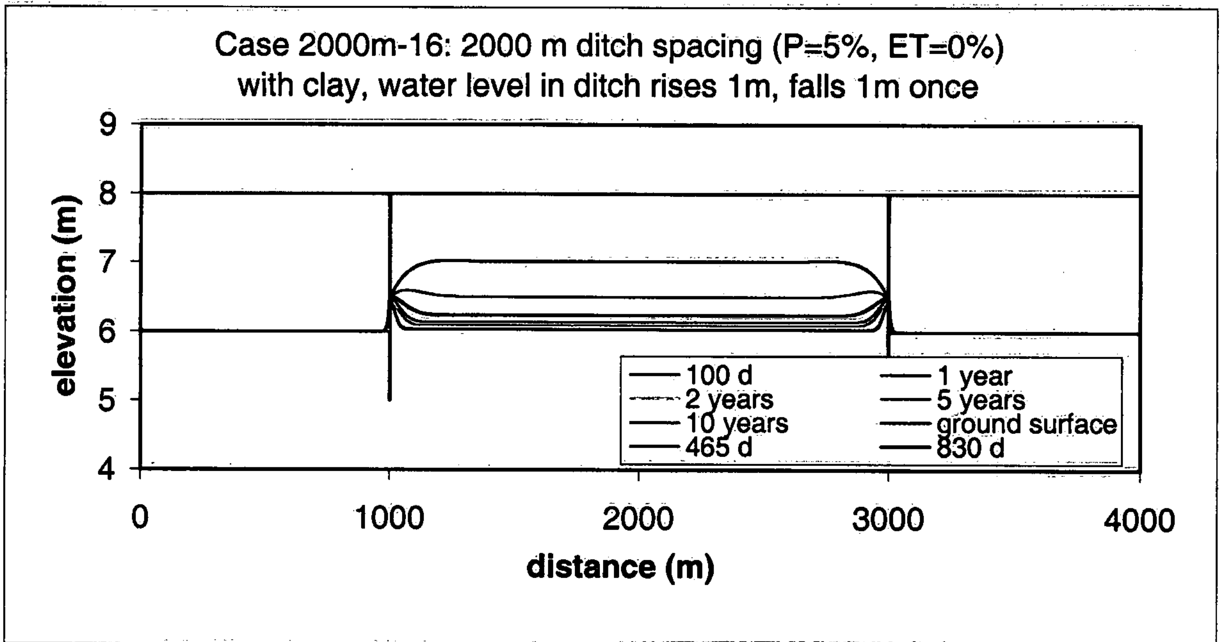

head at water table (100, 250, 1000m from ditch)
head (m)
8
7
6
0
365
730
1095
1460
1825
2190
2555
2920
3285
3650
time (days)
clay-100m
clay-250m
clay-1000m
100m
250m
1000m

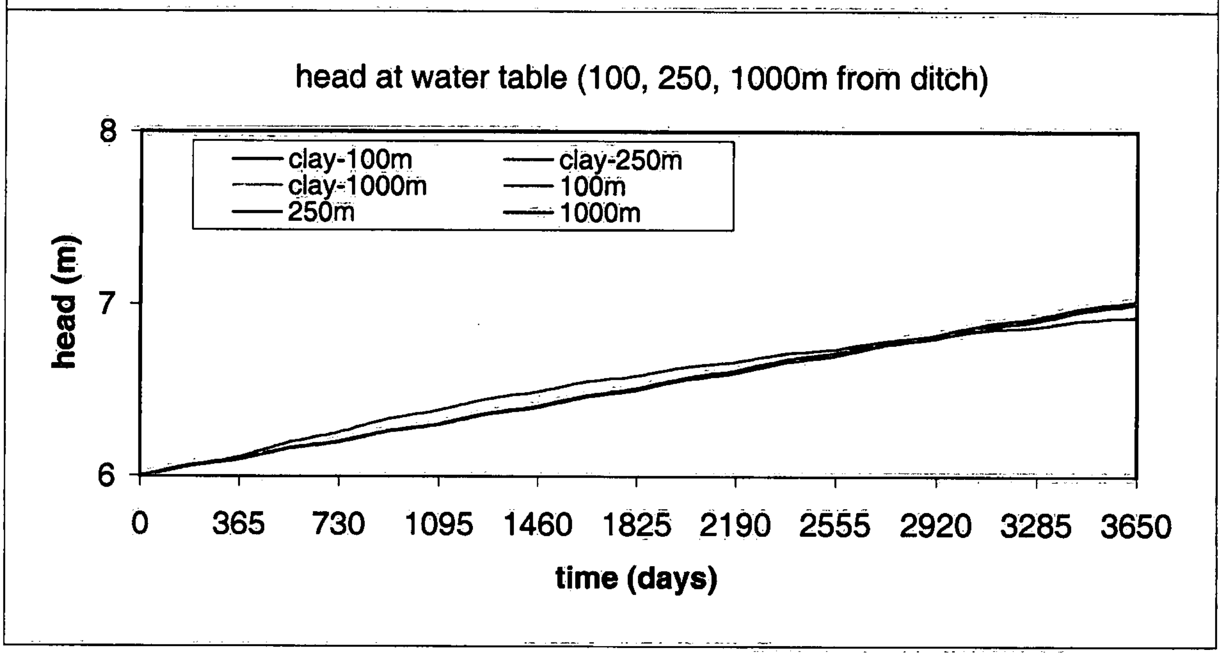


Case 2000m-15; 2000 m ditch spacing (P=100%, ET=100%)
with clay, water level in ditch falls only once
elevation (m)
13
12
11
10
9
8
7
6
5
4
2000
3000
4000
distance (m)
100 d
1 year
2 years
5 years
10 years
ground surface
465 d
830 d



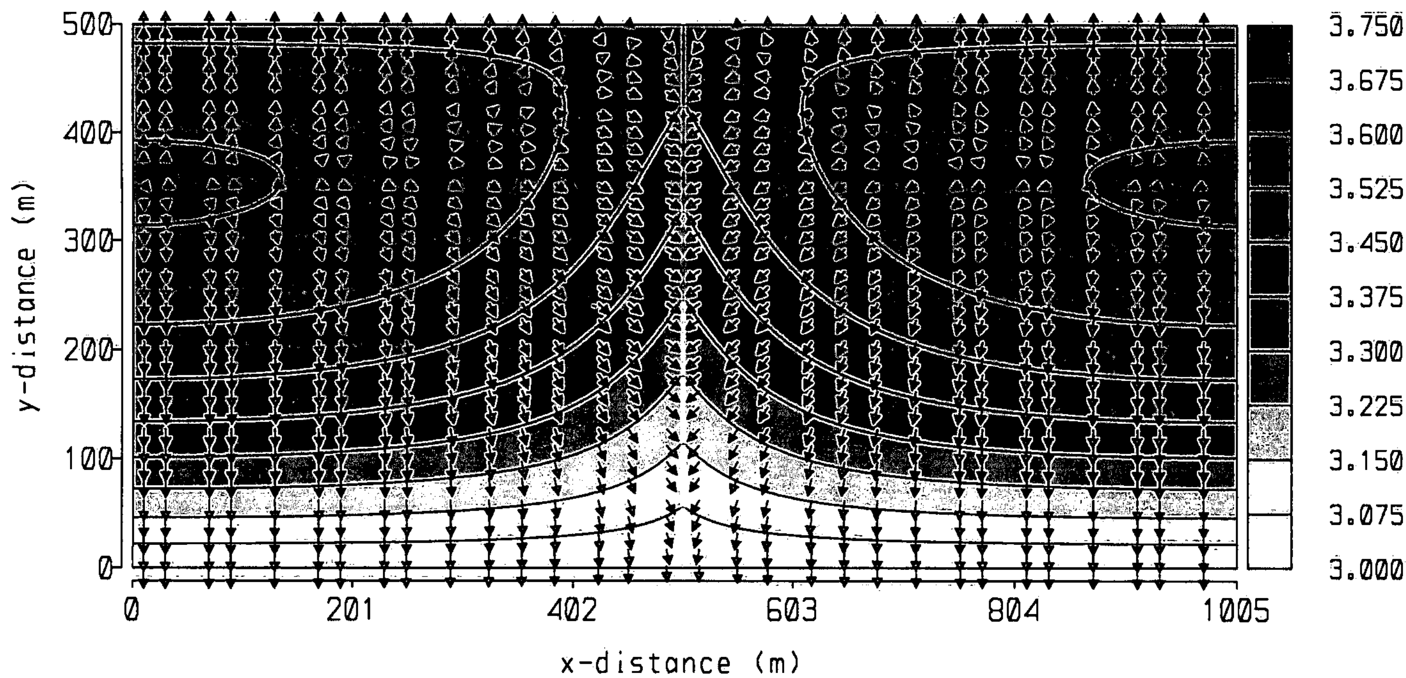
head at water table (100, 250, 1000m from ditch)
head (m)
13
12
11
10
9
8
7
6
clay-100m
clay-250m
clay-1000m
100m
250m
1000m
0
365
730
1095
1460
1825
2190
2555
2920
3285
3650
time (days)

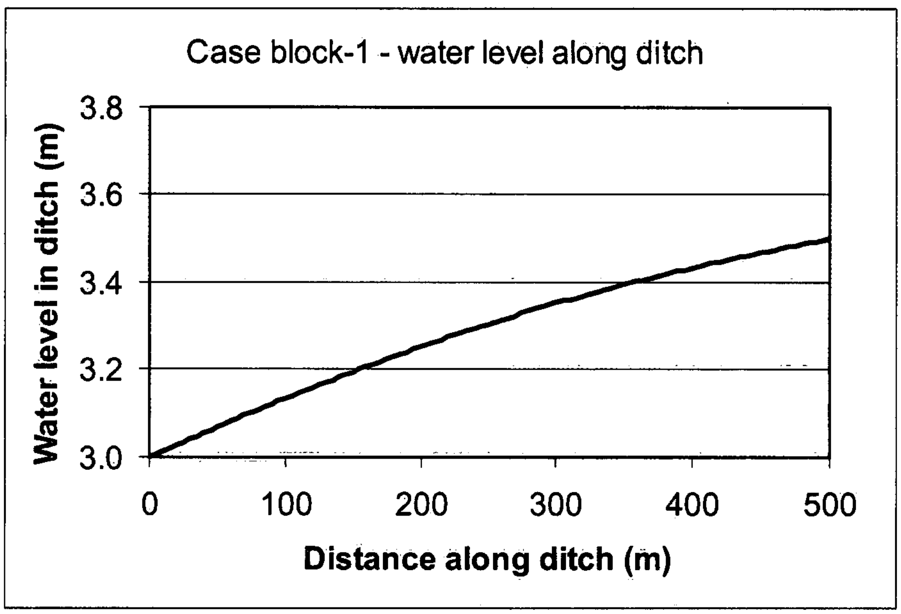

Case 2000m-16: 2000 m ditch spacing (P=5%, ET=0%)
with clay, water level in ditch rises 1m, falls 1m once
elevation (m)
9
8
7
6
5
4
0
1000
2000
3000
4000
distance (m)
100 d
1 year
2 years
5 years
10 years
ground surface
465 d
830 d

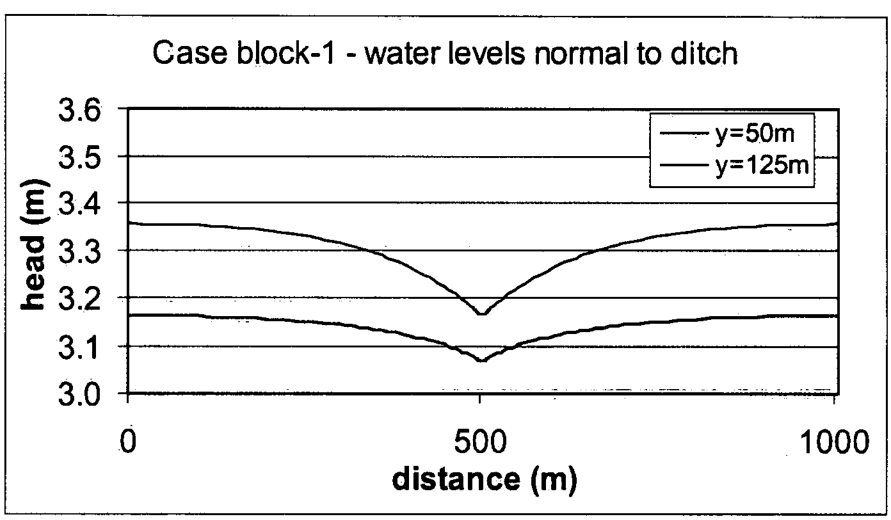

head at water table (100, 250, 1000m from ditch)
head (m)
8
7
6
0
365
730
1095
1460
1825
2190
2555
2920
3285
3650
time (days)
clay-100m
clay-250m
clay-1000m
100m
250m
1000m

Appendix 5:

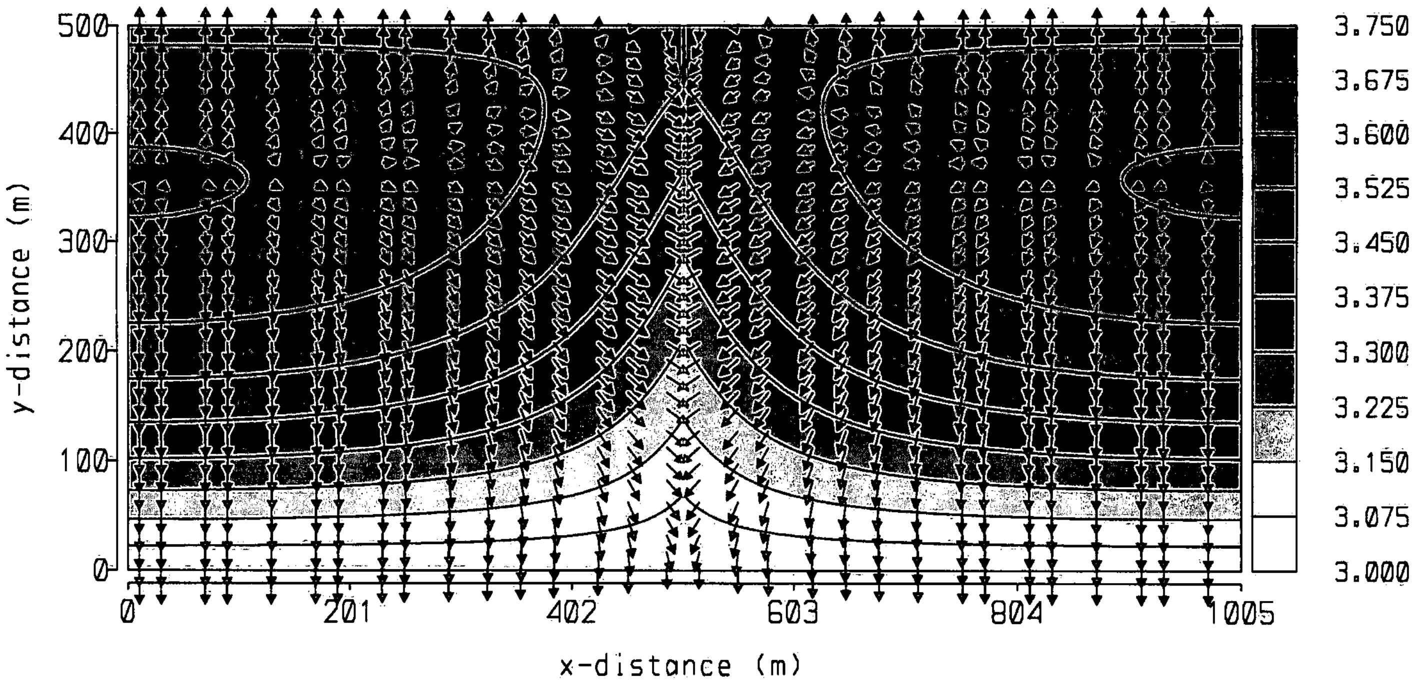
Impact of Blockages within the Drainage Ditch on the Water Table

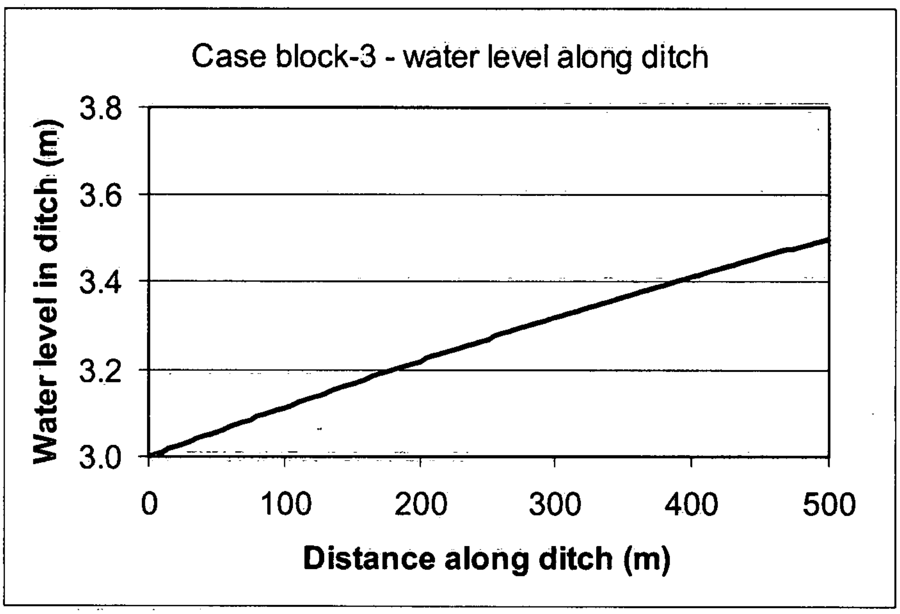


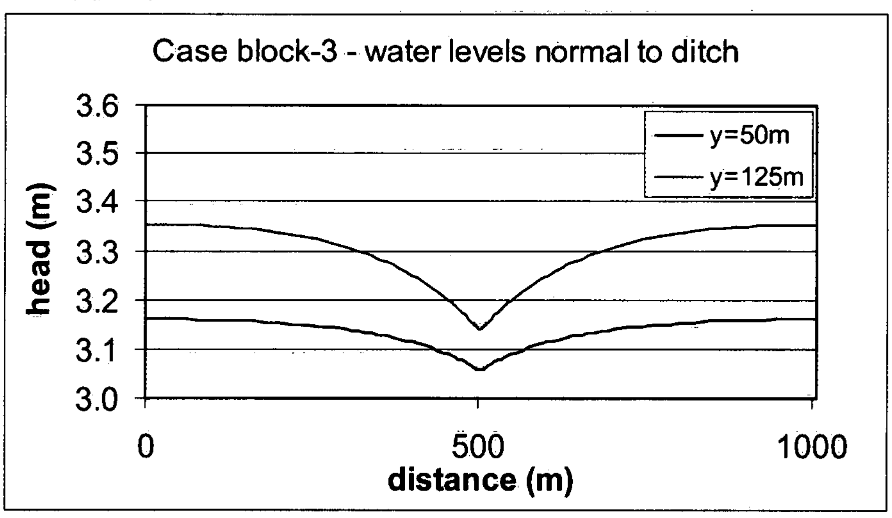




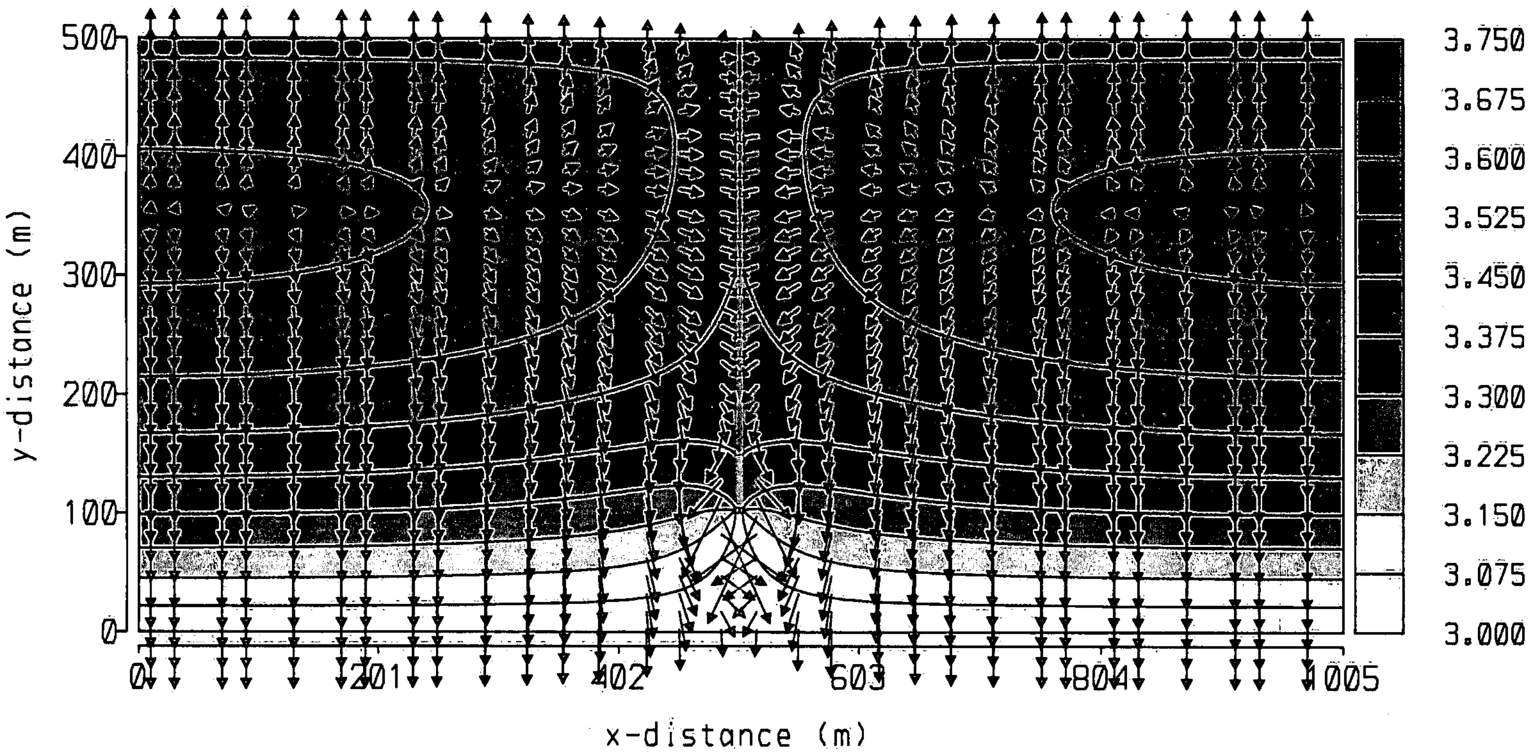
Case block-1: Full boundary conditions, 1m drain, no blockage

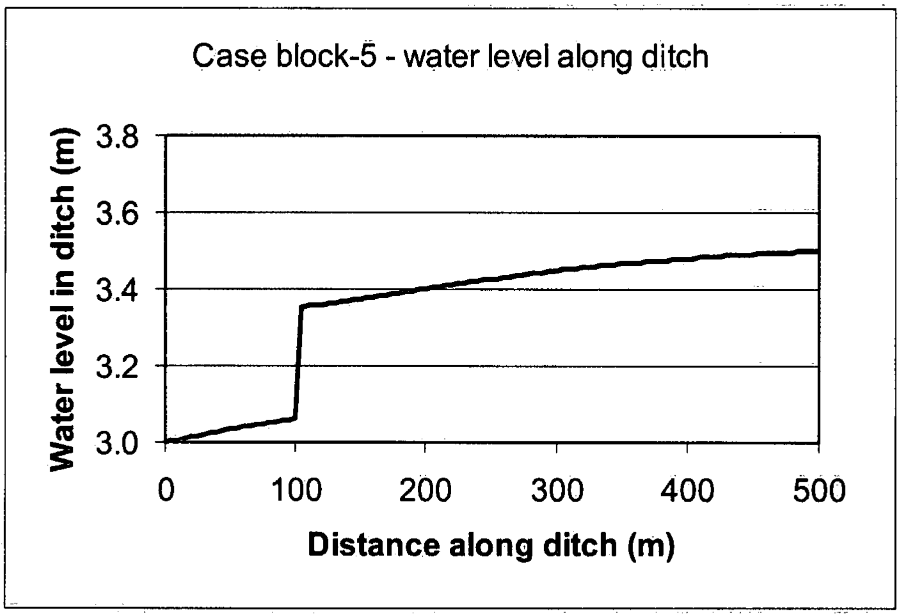


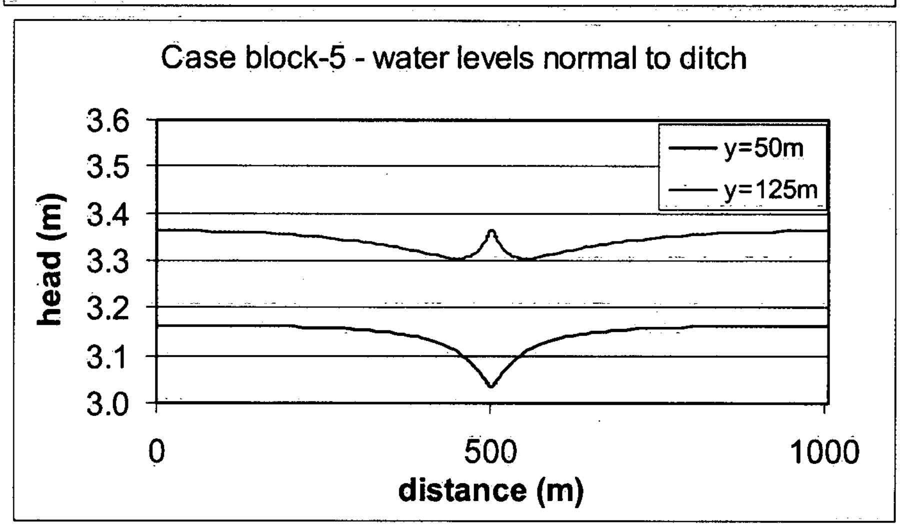




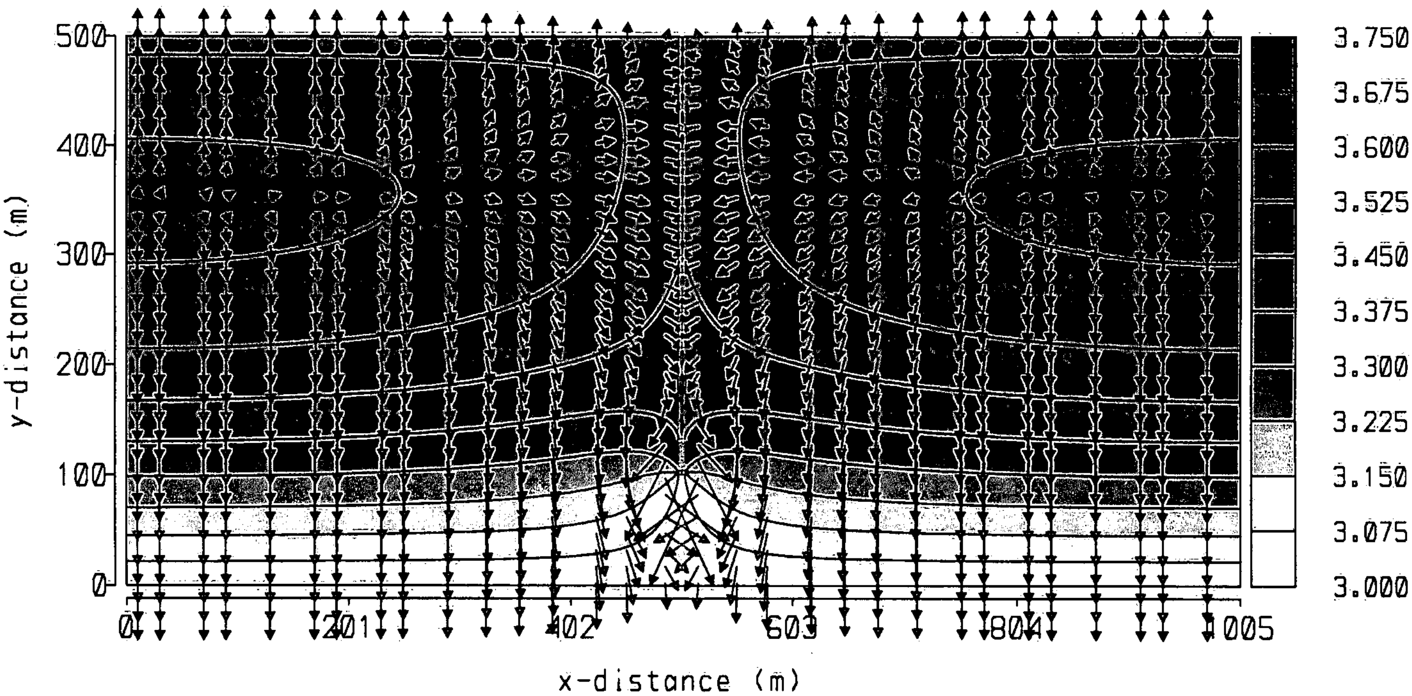
Case block-2: Full boundary conditions, 3m drain, no blockage.

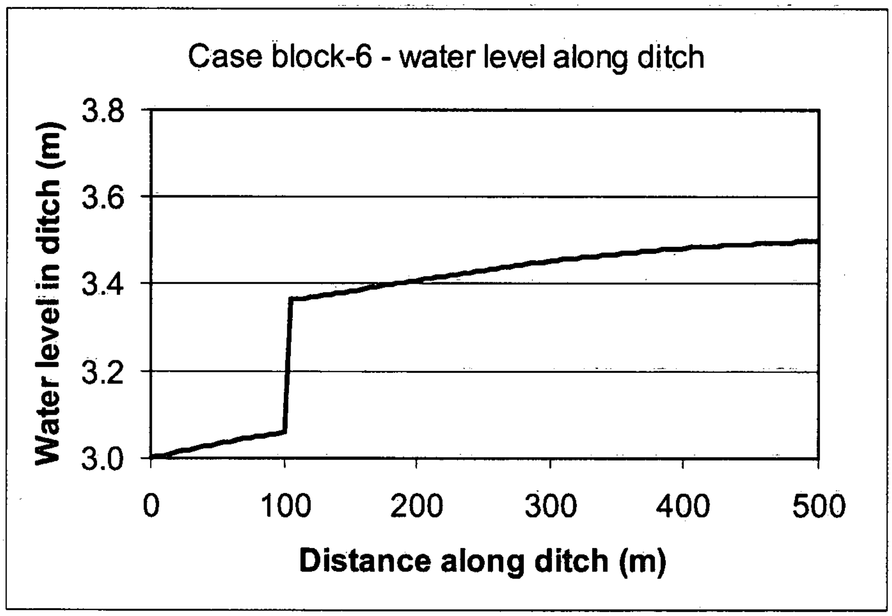


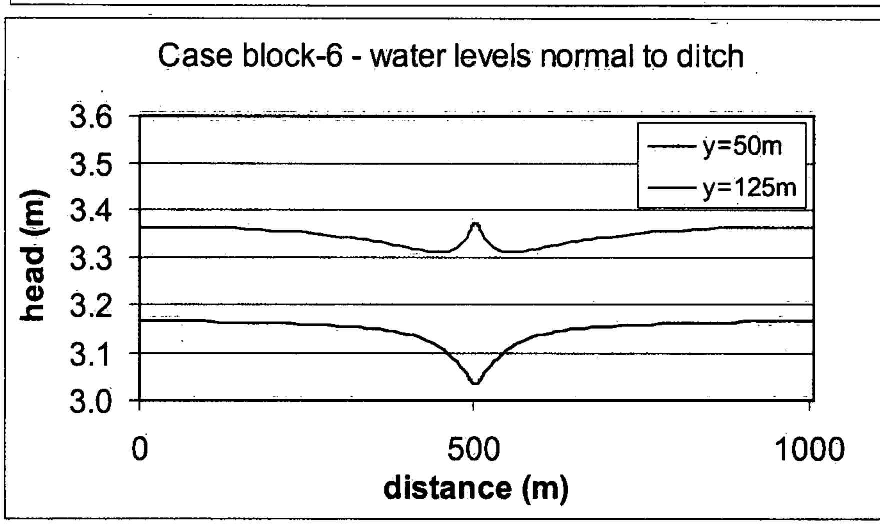




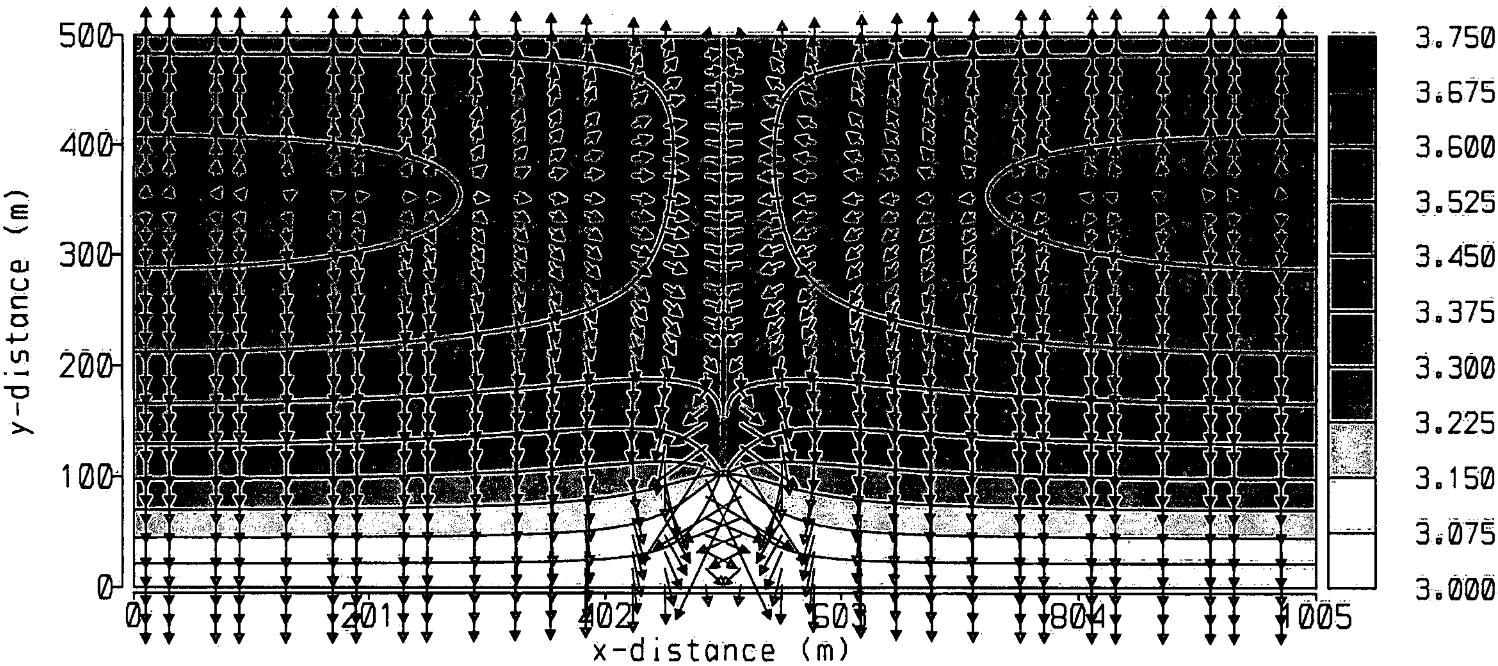
Case block-3: Full boundary conditions, 1m drain,5m blockage at y=100-105m (K_{block}=K_{peat}).

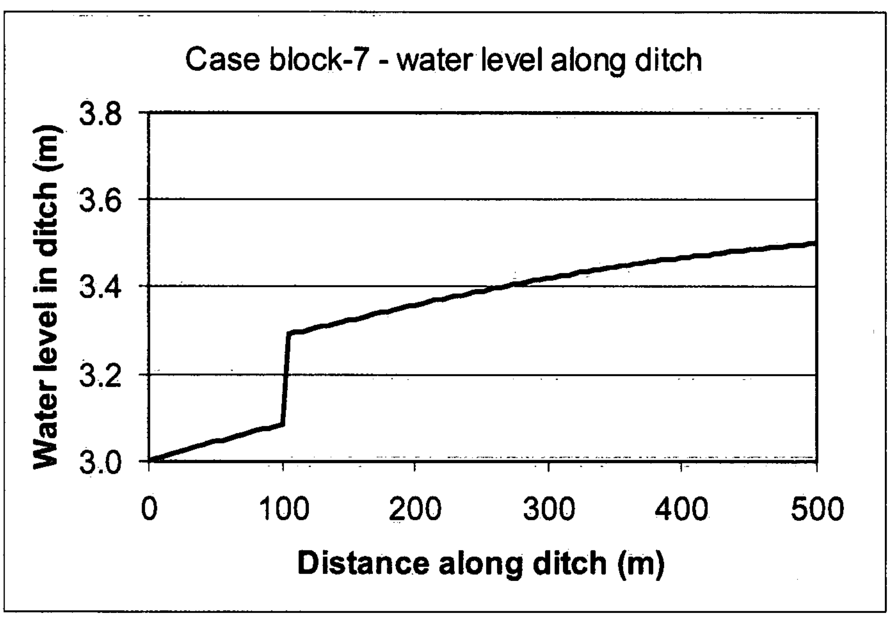


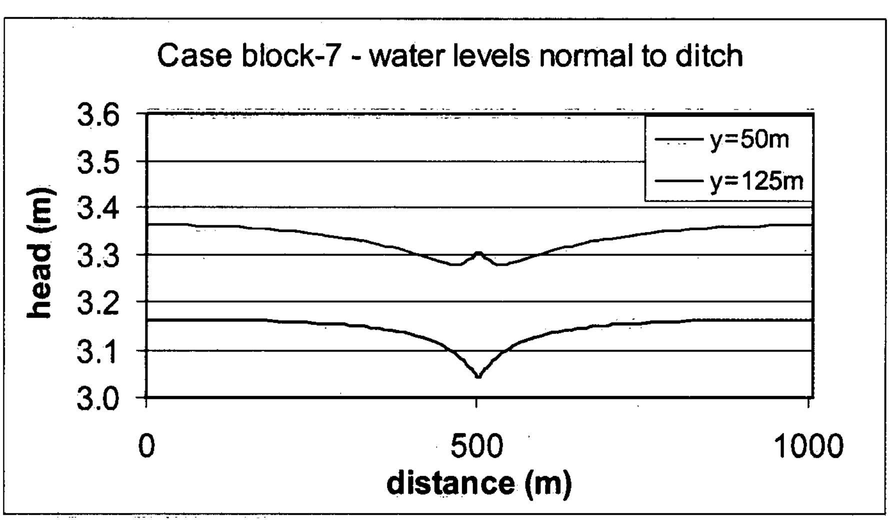




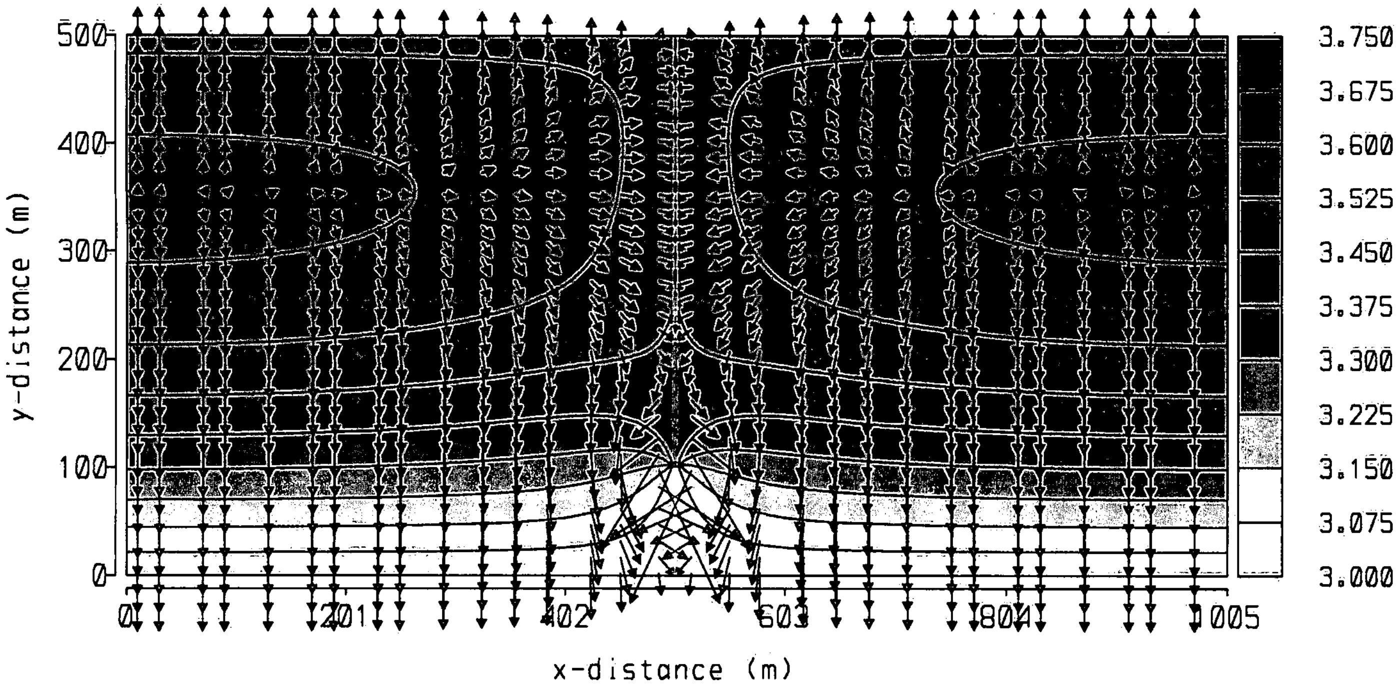
Case block-4 :Full boundary conditions, 1m drain,5m blockage at y=100-105m ($K_{block}=0.1*K_{peat}$).

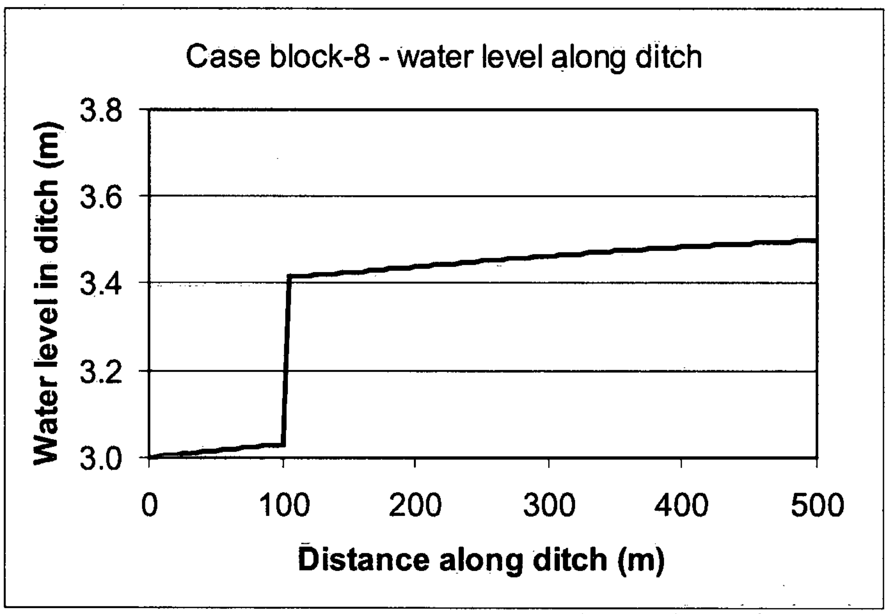


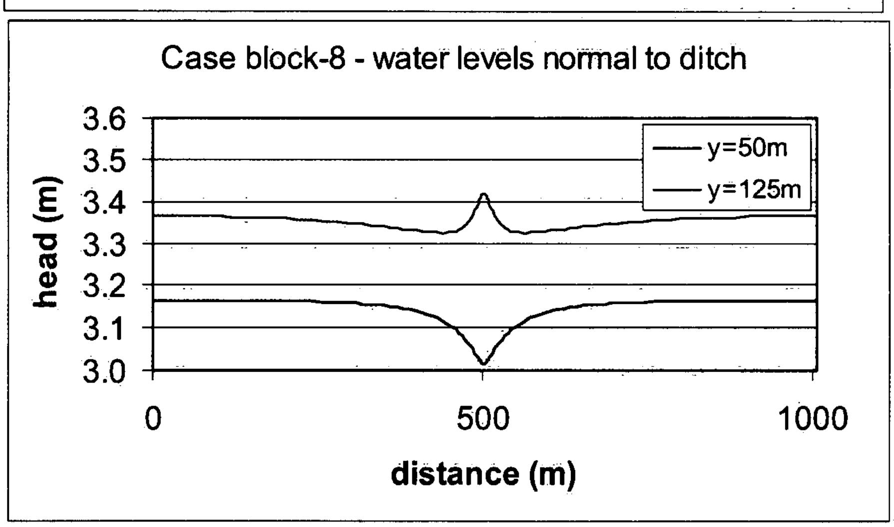




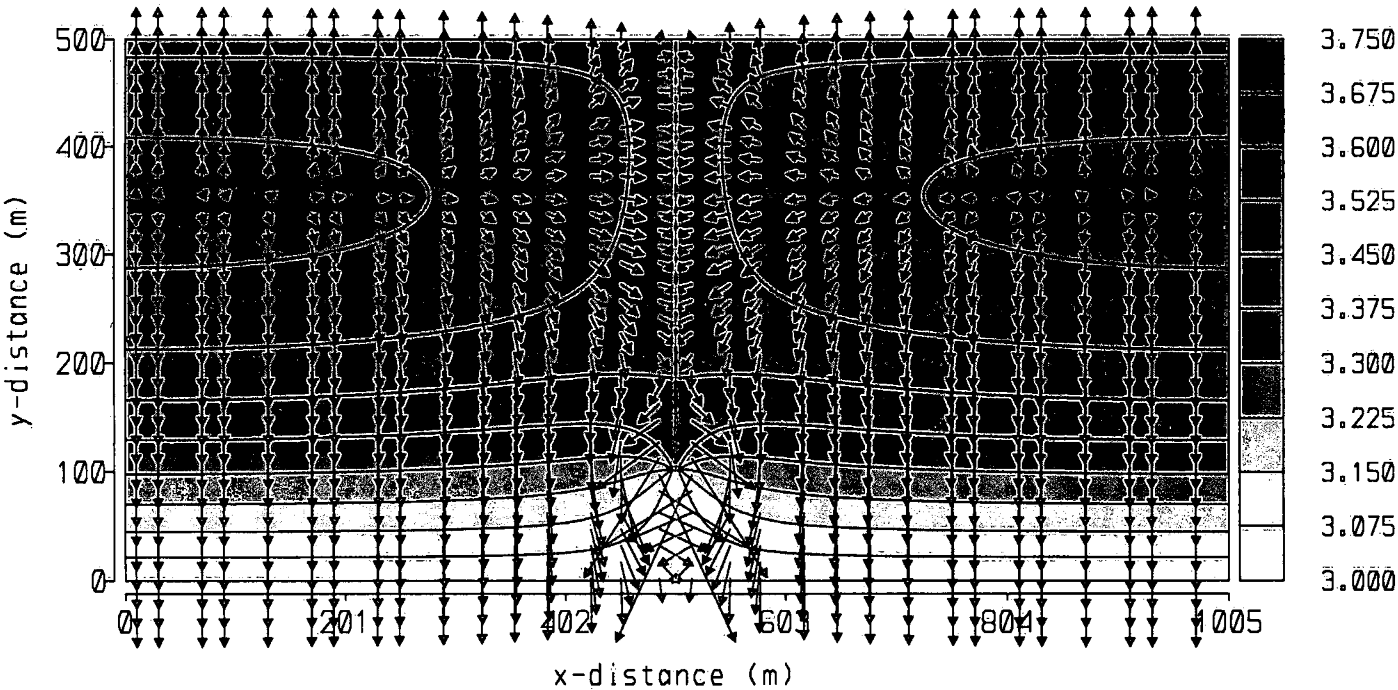
Case block-5: Full boundary conditions, 1m drain,5m blockage at y=100-105m (K_{block}=10*K_{peat}).

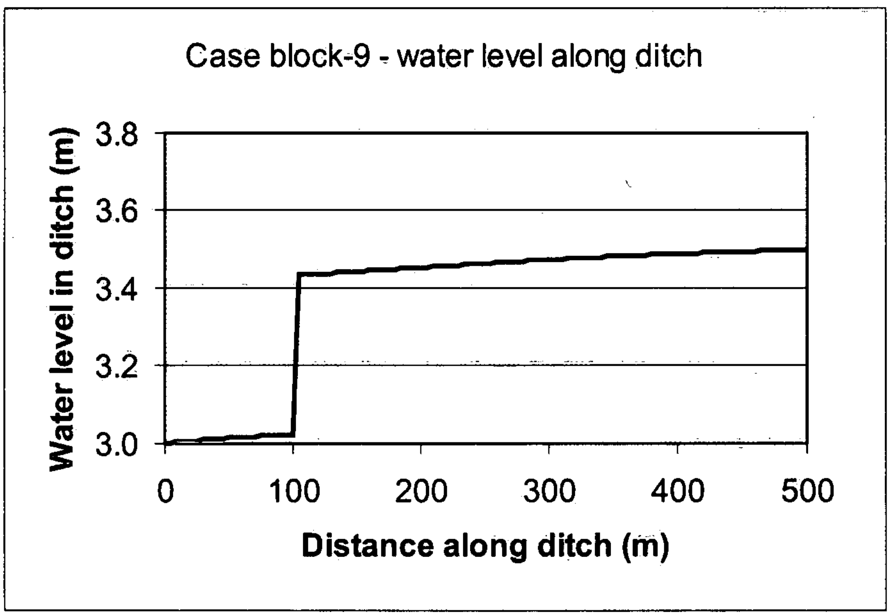


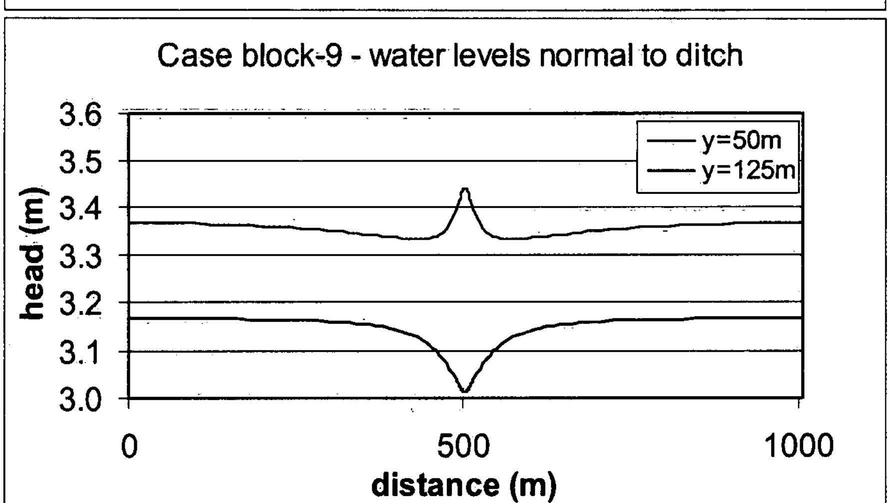




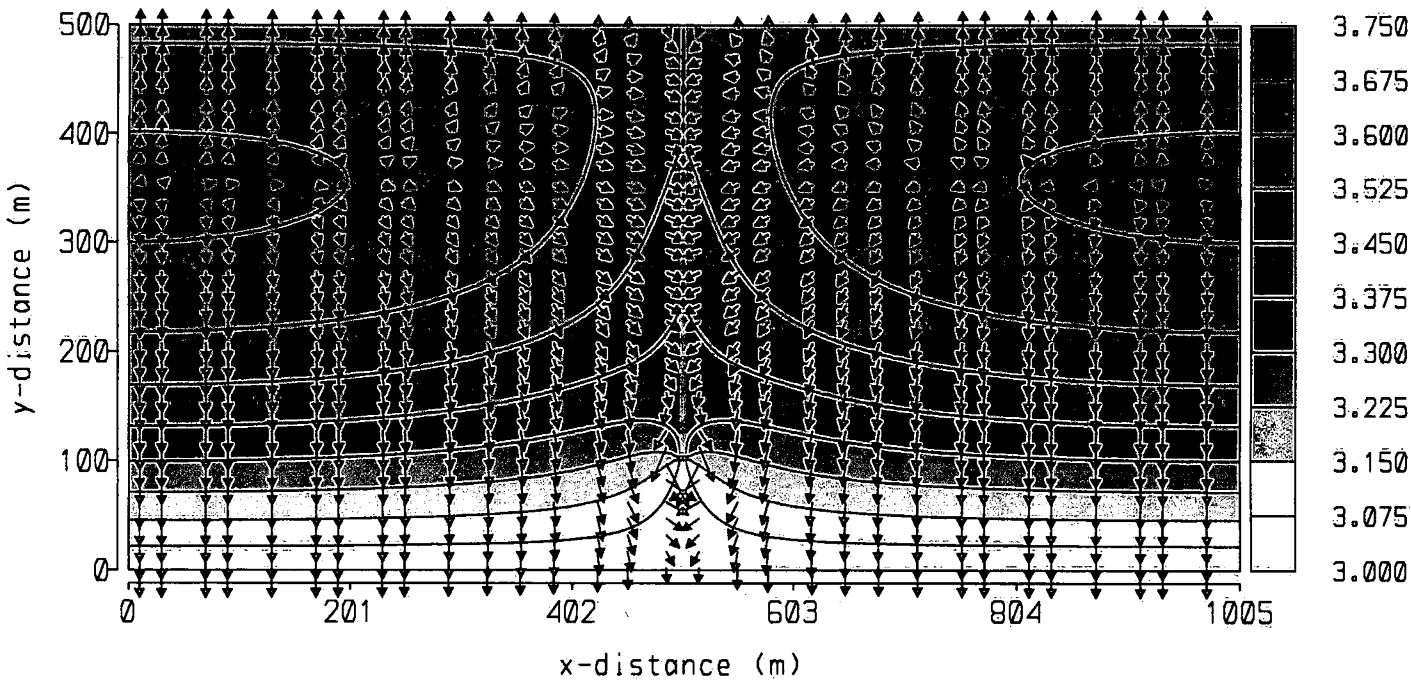
Case block-6: Full boundary conditions, 3m drain, 5m blockage at y=100-105m (K_{block}=K_{peat}).

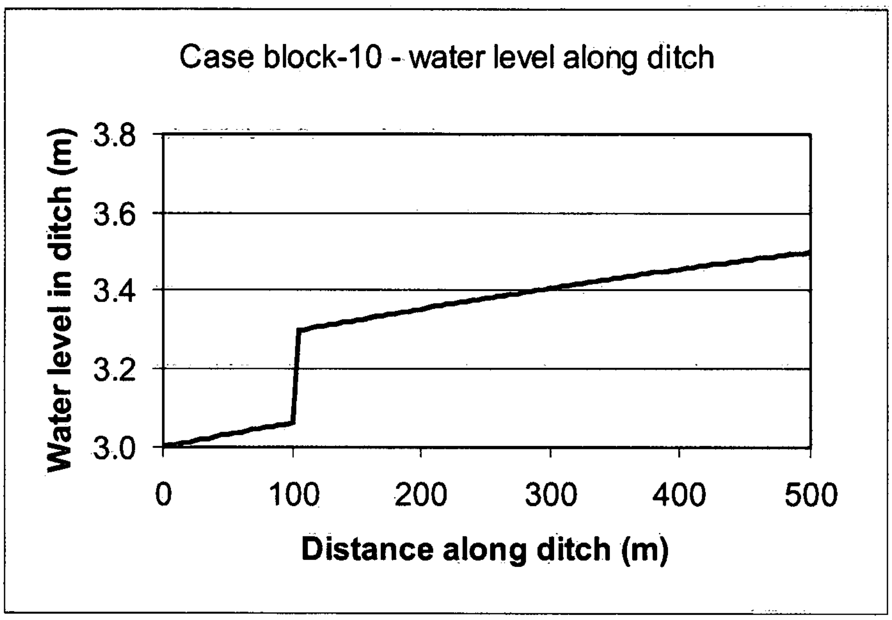


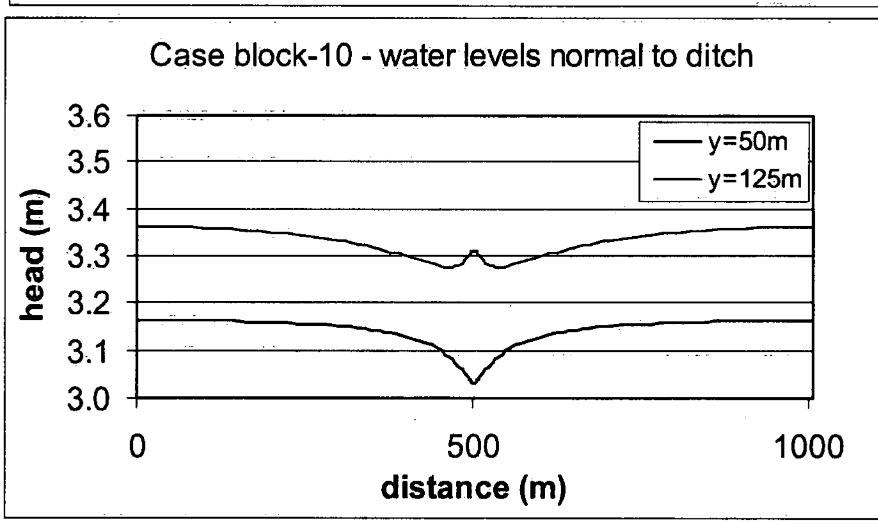




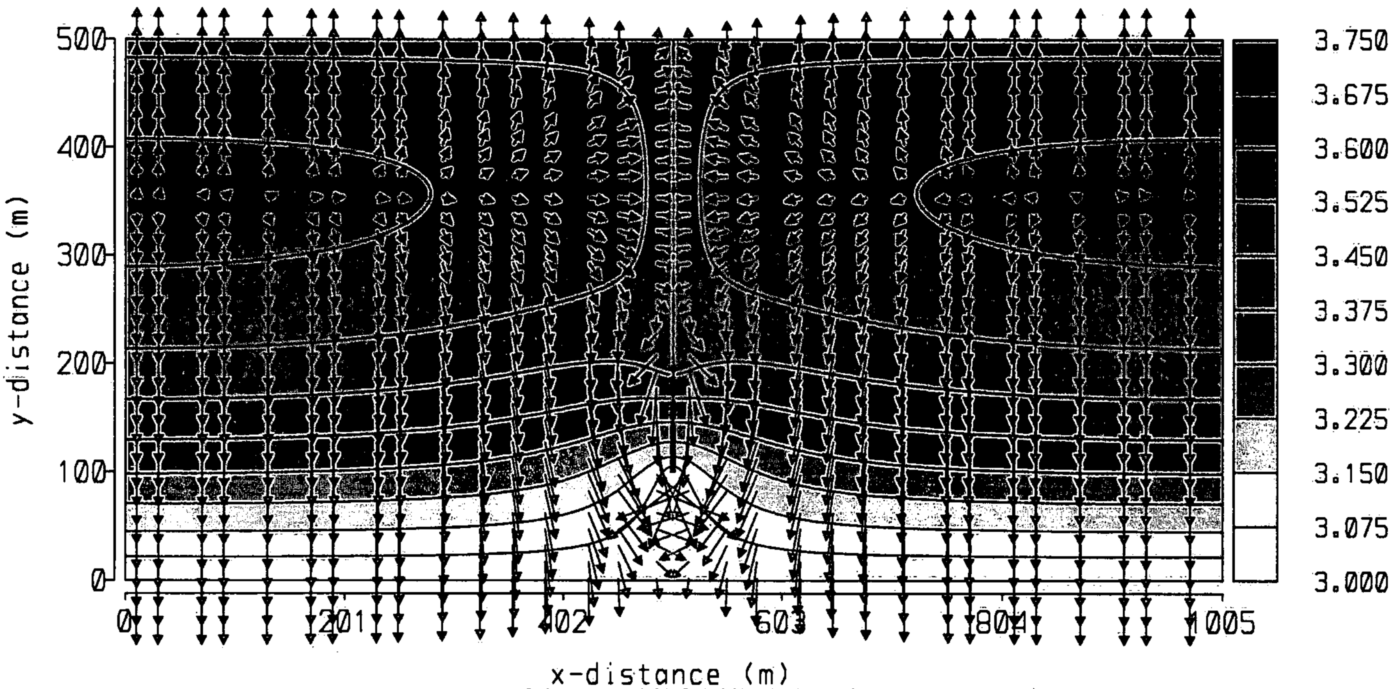
Case block-7: Full boundary conditions, 3m drain, 5m blockage at y=100-105m (K_{block}=0.1*K_{peat}).

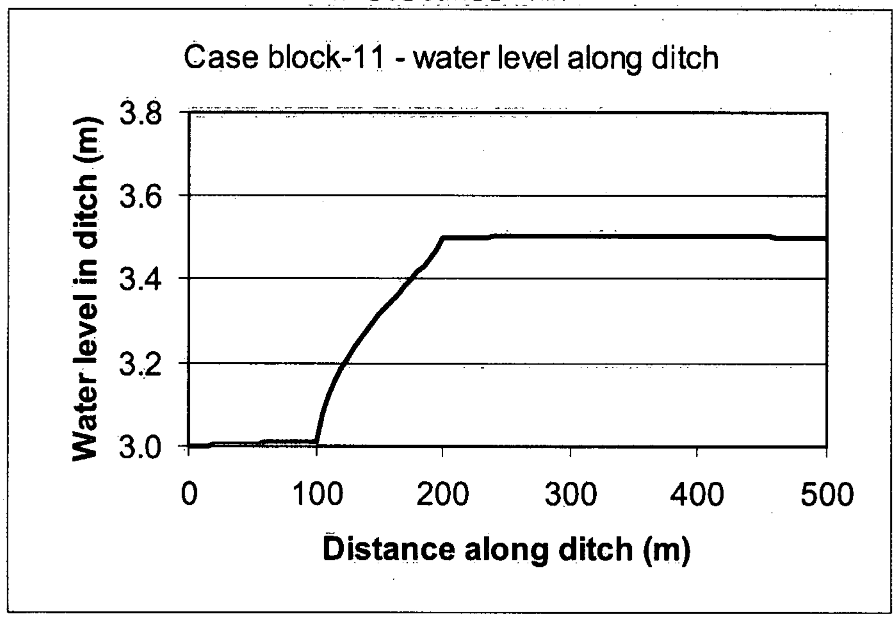


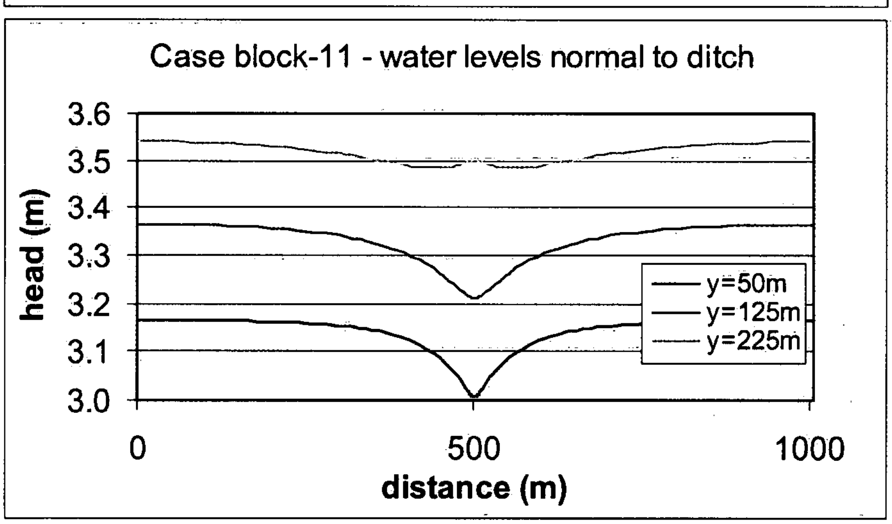




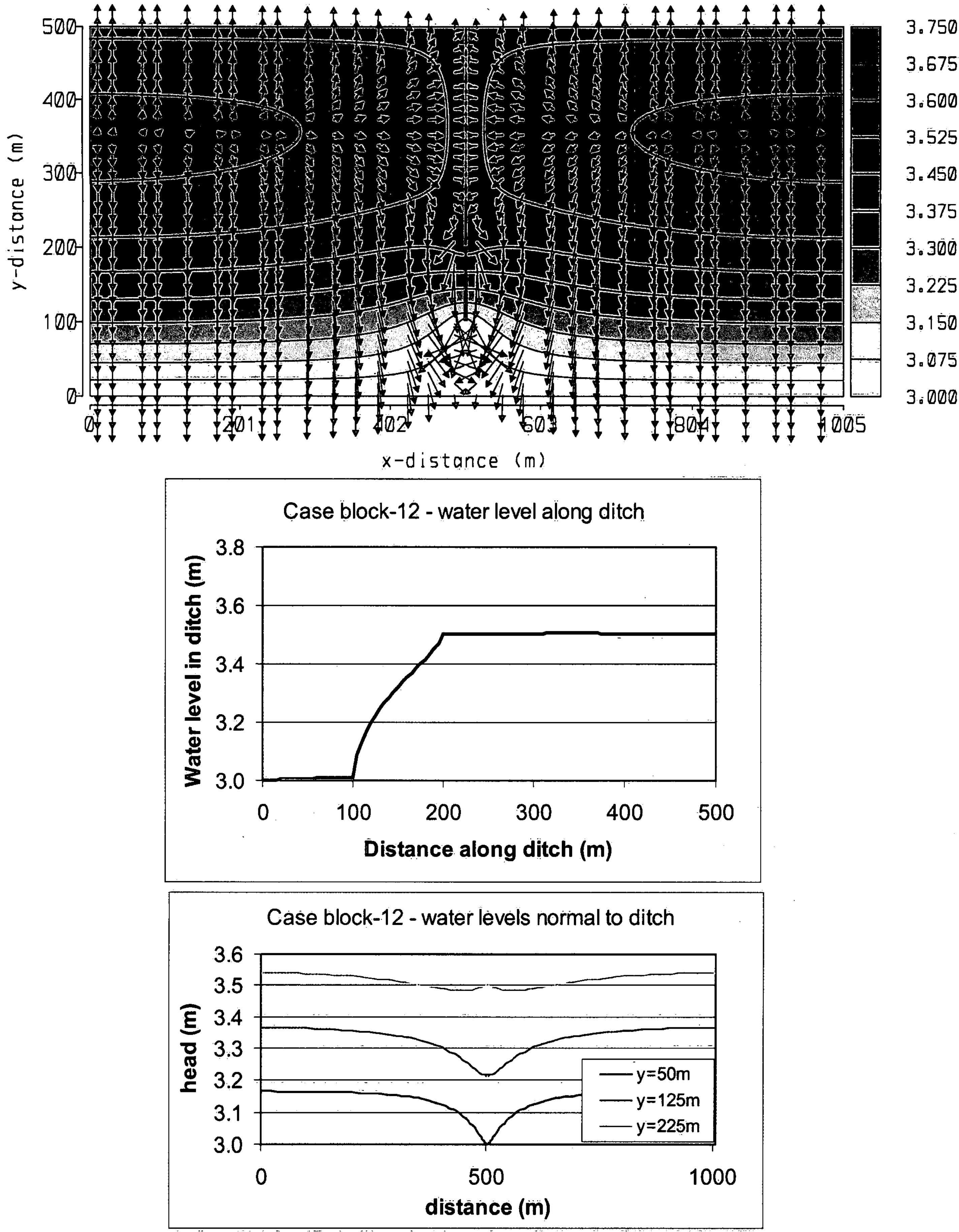
Case block-8:Full boundary conditions, 3m drain,5m blockage at y=100-105m (K_{block}=10*K_{peat}).



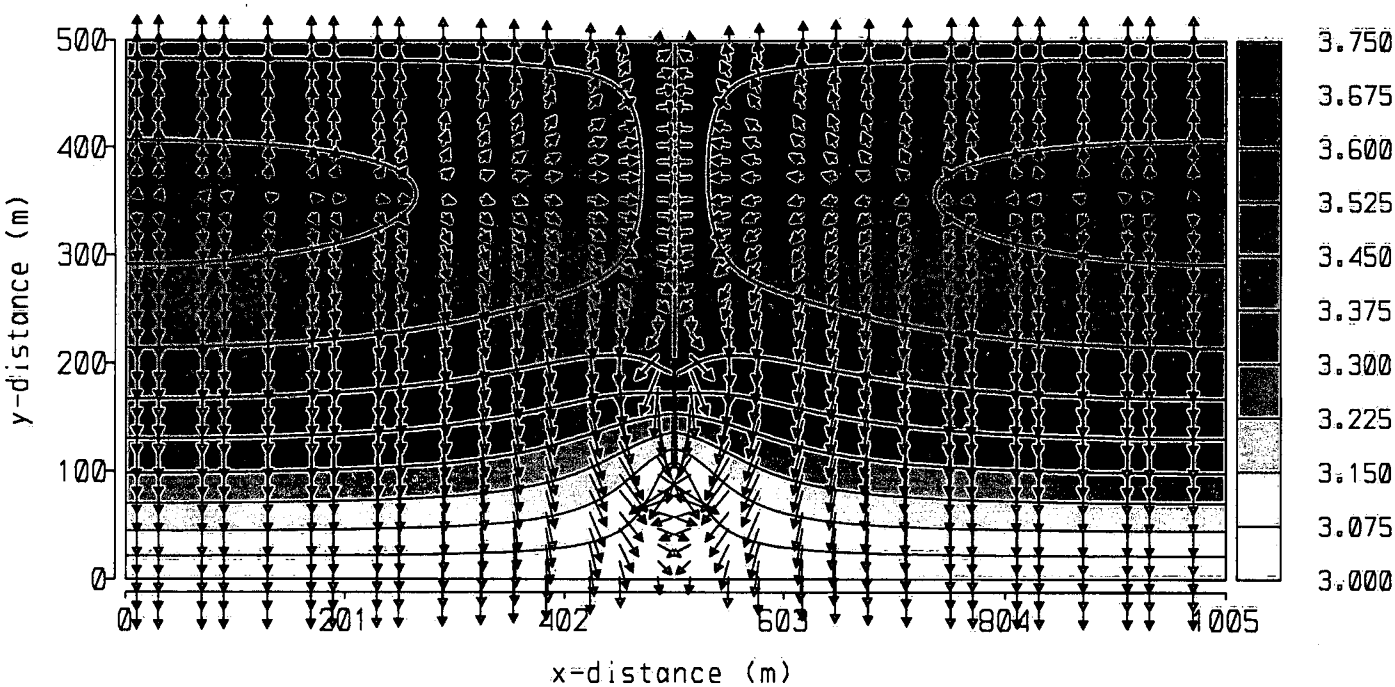


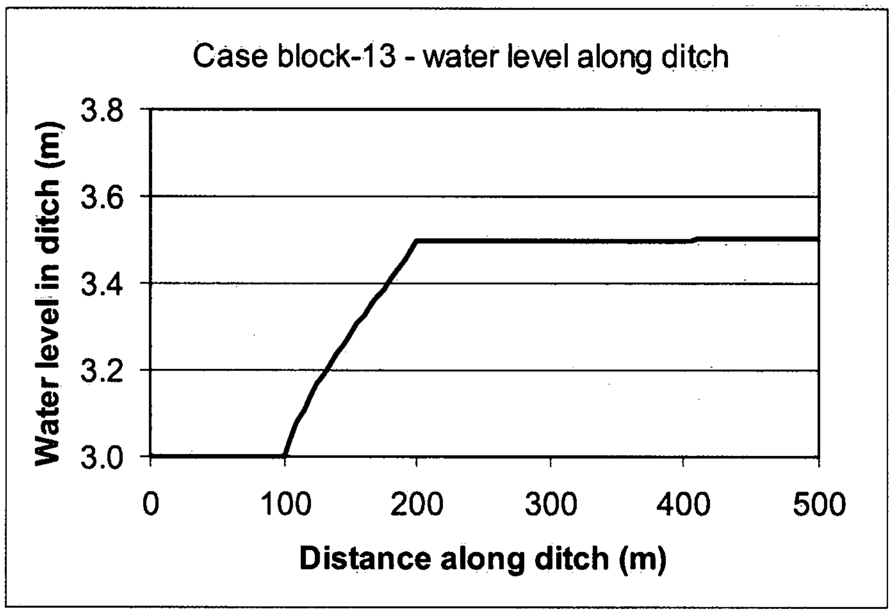


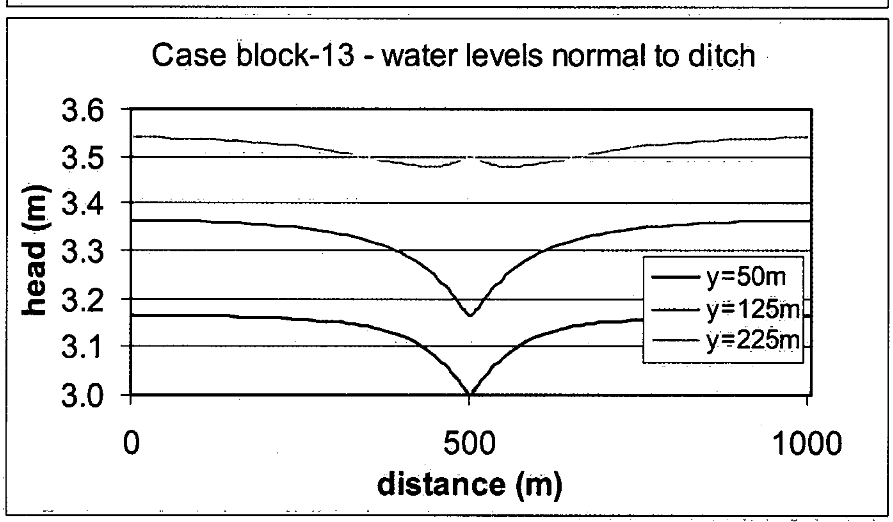
Case block-9:Full boundary conditions, 3m drain, 100m blockage at y=100-200m ($K_{block} = K_{peat}$).



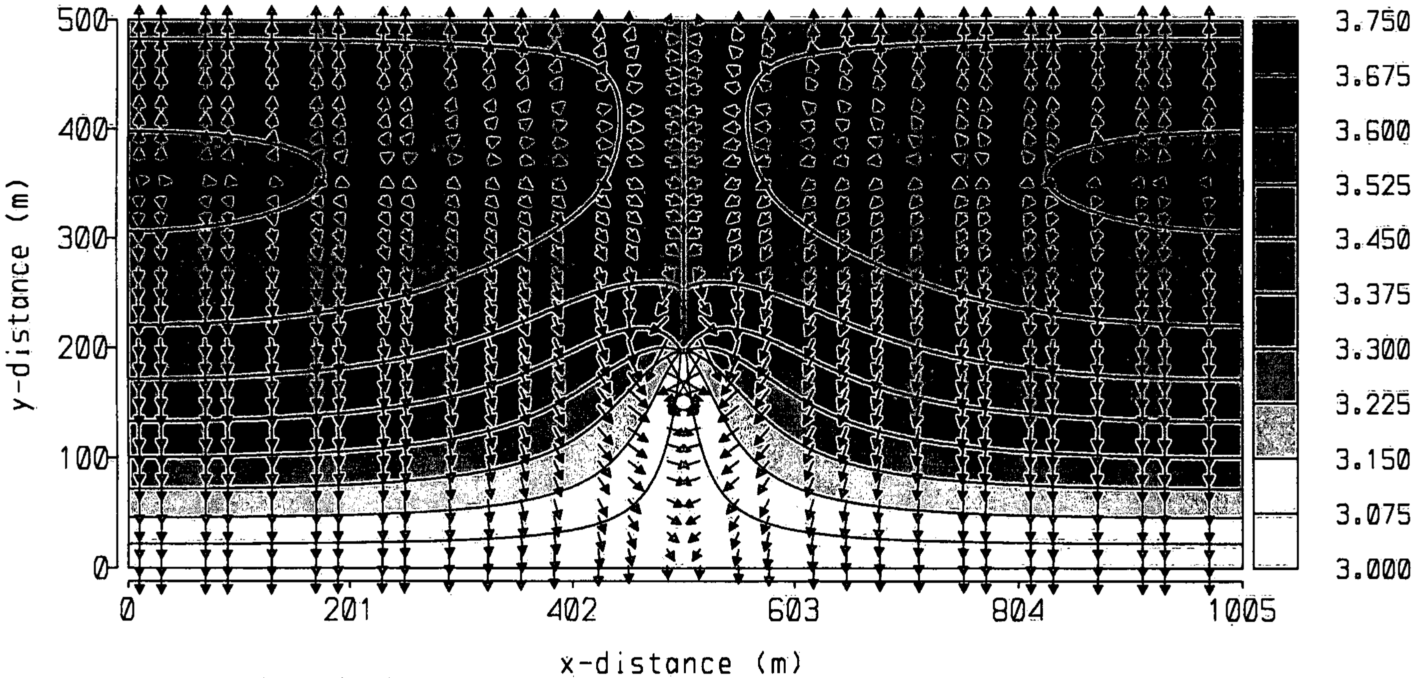
Case block-10:Full boundary conditions, 3m drain, 100m blockage at y=100-200m (K_{block}=0.1*K_{peat}).

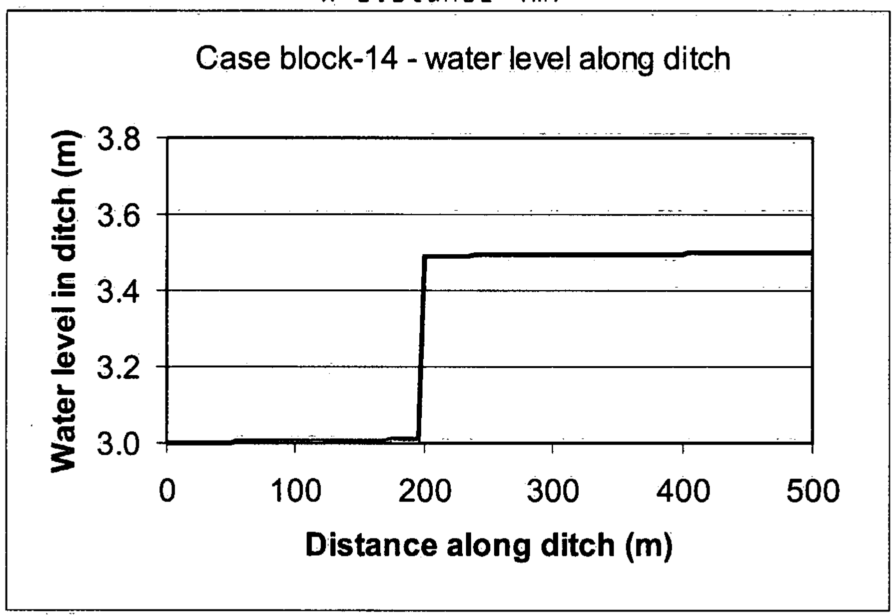


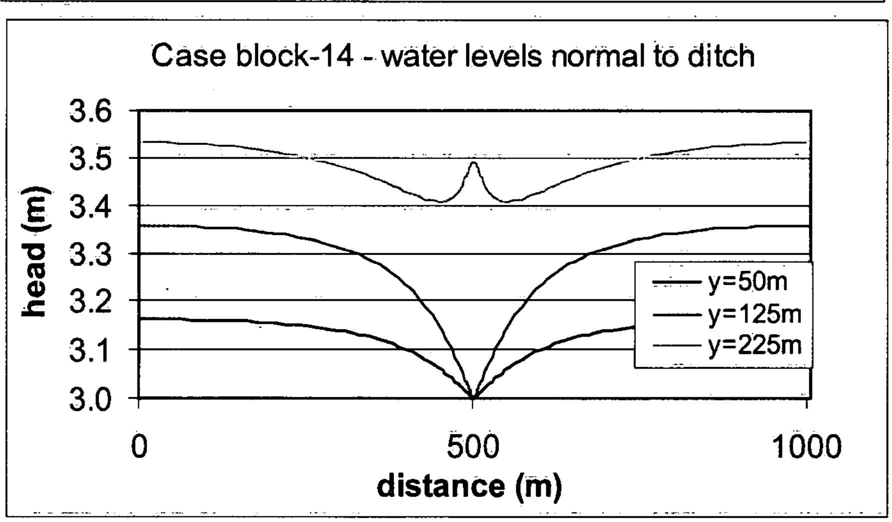




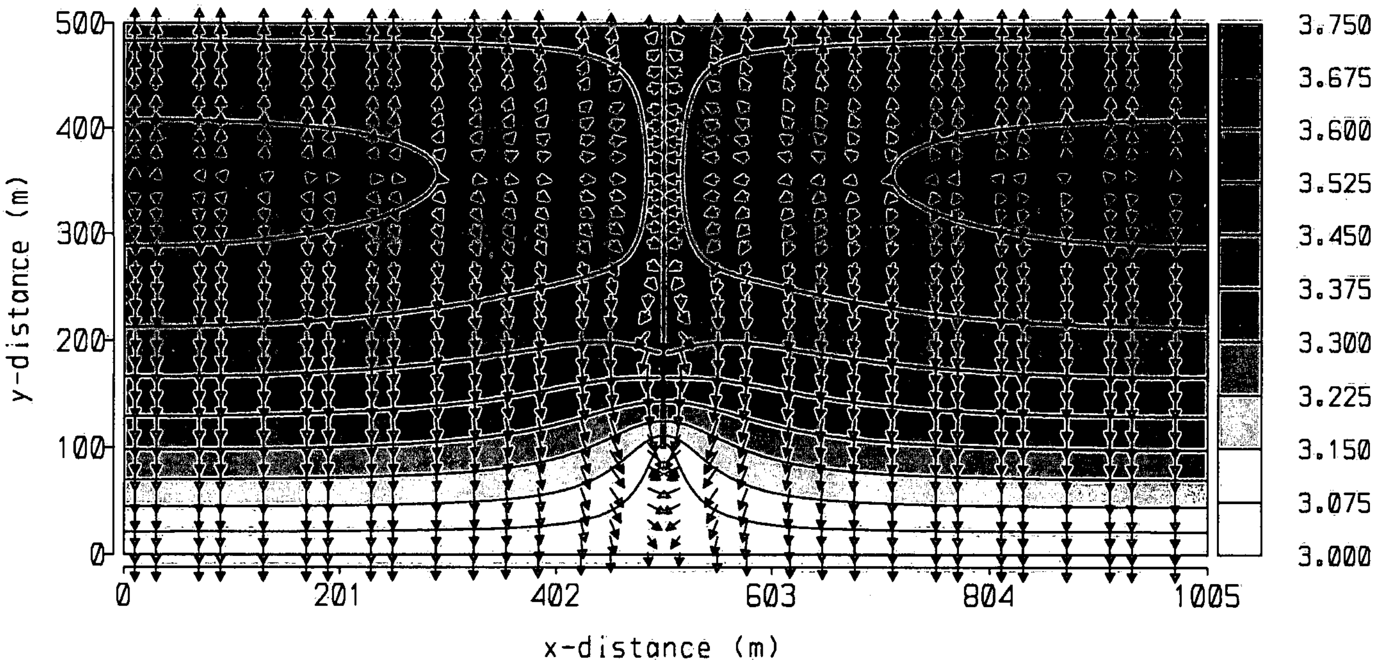
Case block-11: Full boundary conditions, 3m drain, 100m blockage at y=100-200m (K_{block}=10*K_{peat}).

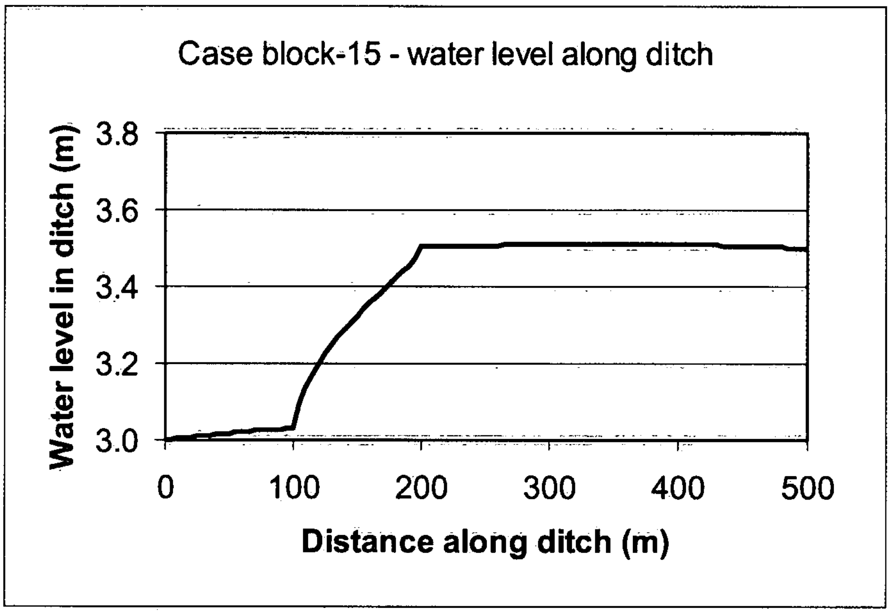


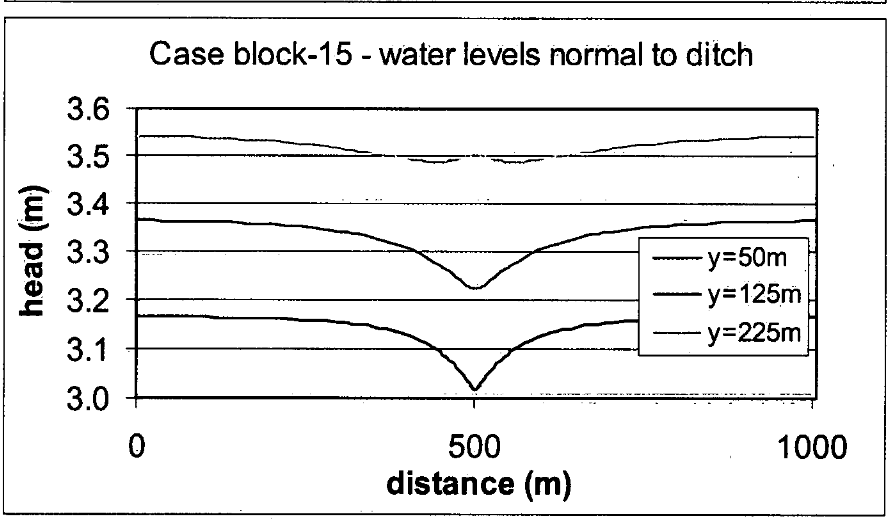




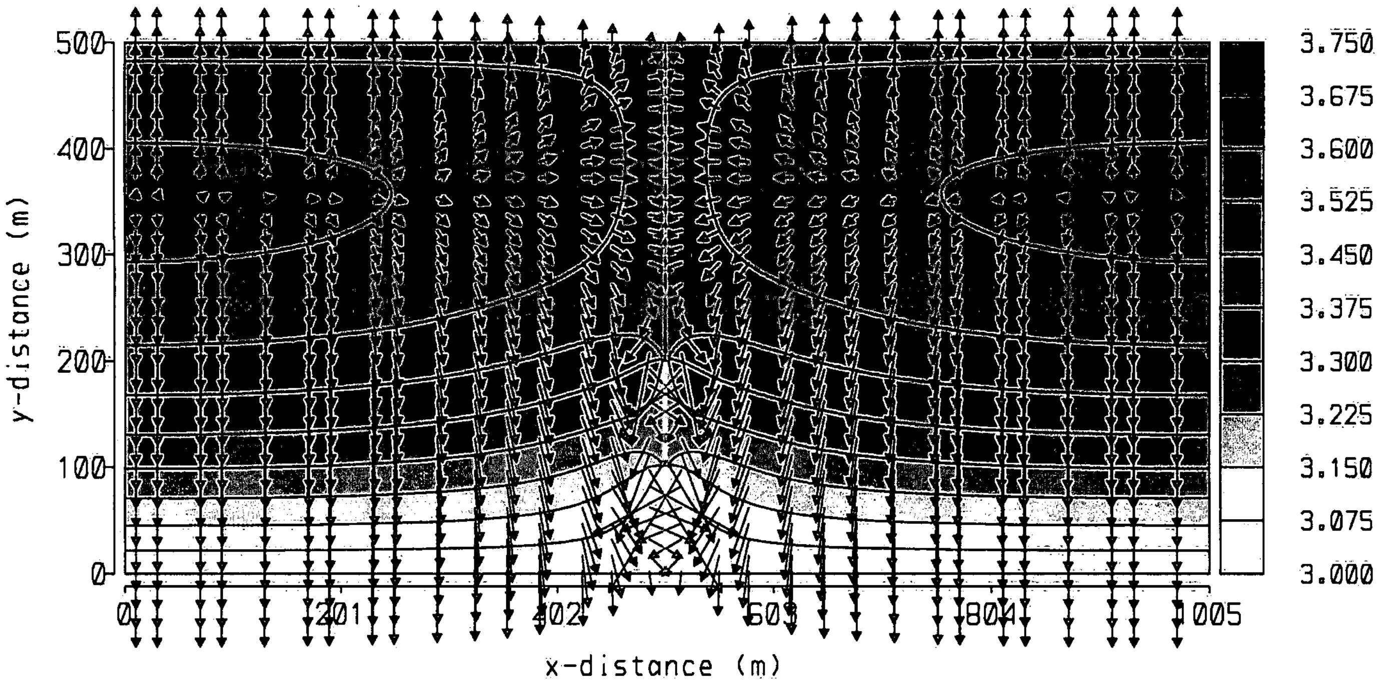
Case block-12: Full boundary conditions, 3m drain, 5m blockage at y=195-200m ($K_{block} = K_{peat}$).

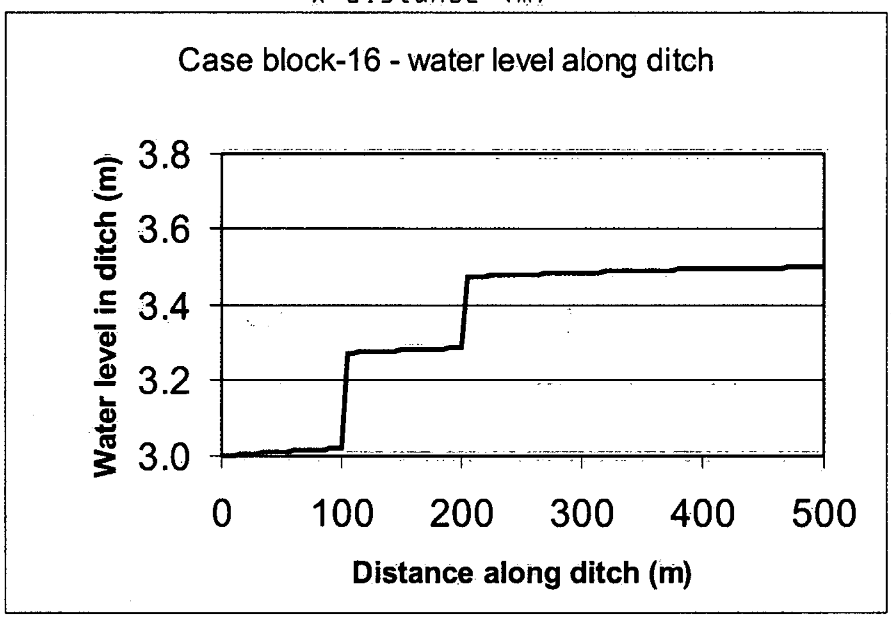


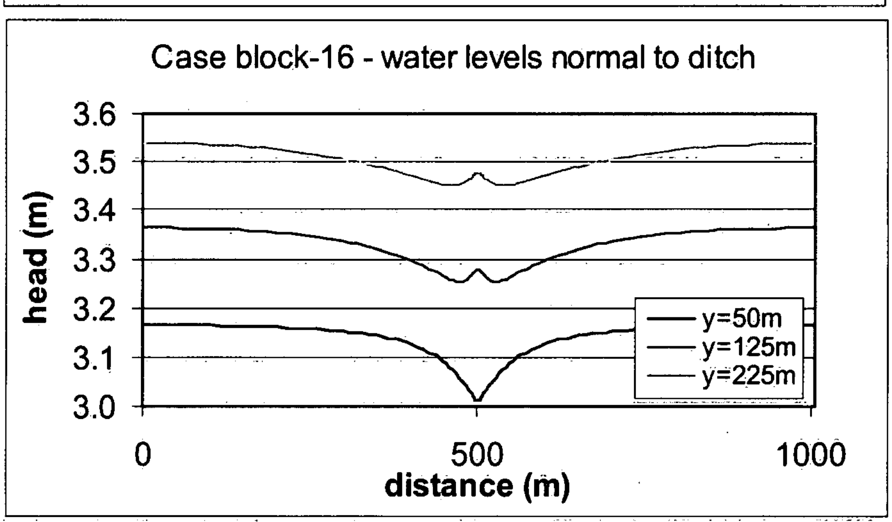




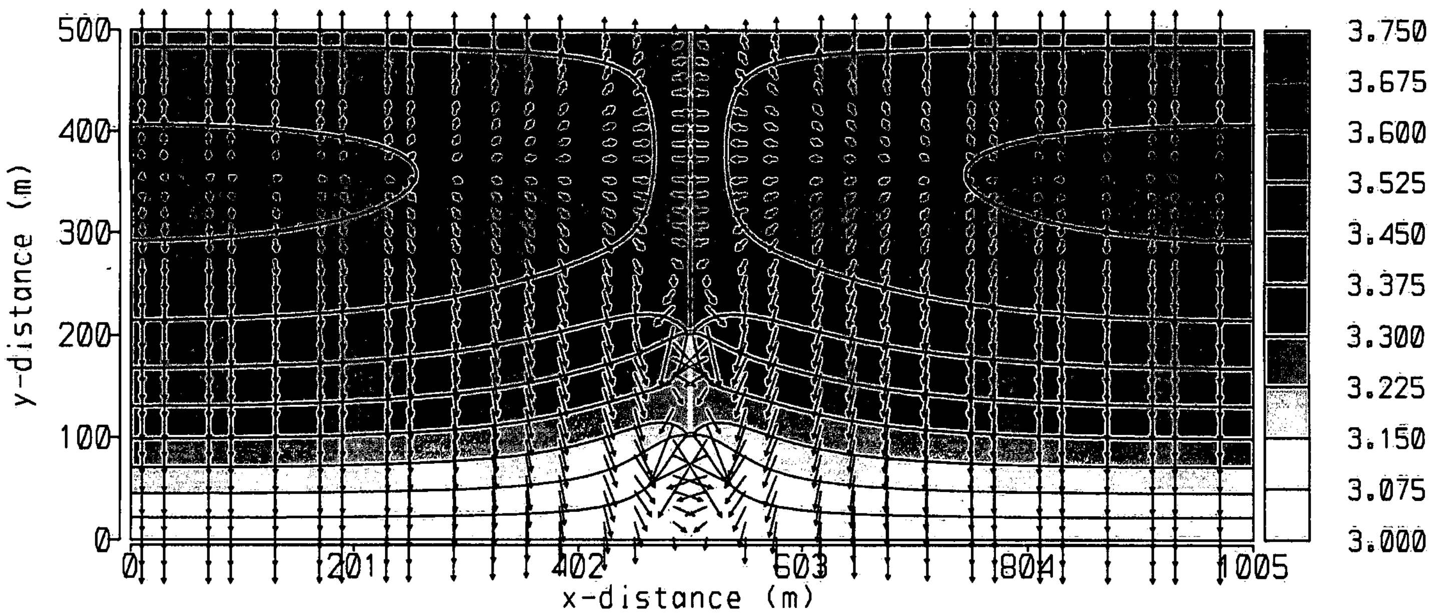
Case block-13: Full boundary conditions, 1m drain, 100m blockage at y=100-200m ($K_{block} = K_{peat}$).

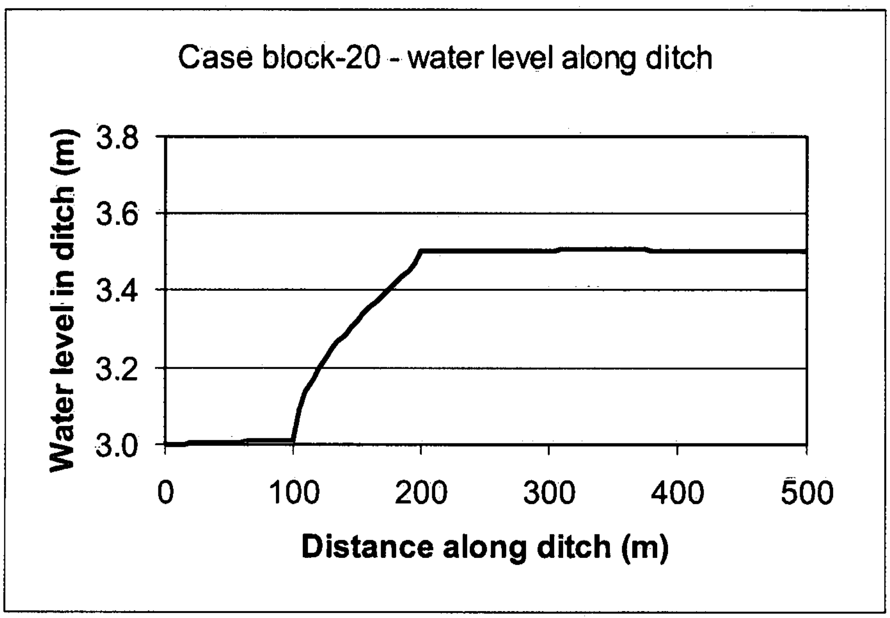


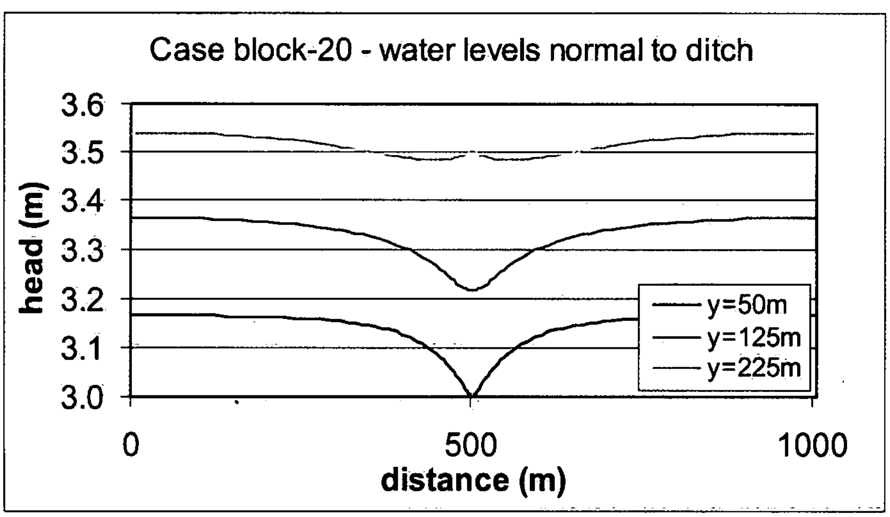




Case block-14: Full boundary conditions, 3m drain, 2x5m blockages at y=100-105m, y=200-205m ($K_{block} = K_{peat}$).







Case block-15: Full boundary conditions, 1m drain, 2x5m blockages at y=100-105m, y=200-205m ($K_{block} = K_{peat}$).

NATIONAL WATER RESEARCH INSTITUTE

INSTITUT NATIONAL DE RECHERCHE SUR LES EAUX

National Water Research Institute
Environment Canada
Canada Centre for Inland Waters
P.O. Box 5050
867 Lakeshore Road
Burlington, Ontario
Canada L7R 4A6

National Hydrology Research Centre
11 Innovation Boulevard
Saskatoon, Saskatchewan
Canada S7N 3H5

Institut national de recherche sur les eaux
Environnement Canada
Centre canadien des eaux intérieures
Case postale 5050
867, chemin Lakeshore
Burlington; (Ontario)
Canada L7R 4A6

Centre national de recherche en hydrologie
11, boulevard Innovation
Saskatoon; (Saskatchewan)
Canada S7N 3H5