NGU Report 94.010

A Groundwater Vulnerability Study of the Korgen waterworks, Lillehammer kommune

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REPORT

Report no. 94.010	ISSN 0800-3416	Grading: Open

Title:

A Groundwater Vulnerability Study of the Korgen waterworks, Lillehammer kommune

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County: Oppland	Commune: Lillehammer
Map-sheet name (M=1:250.000) Lillehammer	Map-sheet no. and name (M=1:50.000) 1817 II Lillehammer
Deposit name and grid-reference: Korgen/Hovemoen	Number of pages: 21 Price: 145,- Map enclosures: None

Fieldwork carried out: September 1993	Date of report: 27/1/94	Project no.: 63.2608.00	Person responsible:

Summary:

This report has been prepared as part of NGUs contribution to the "Korgen vannverk" project being carried out by Berdal Strømme a.s.. This project forms part of the ENSIS VANN project connected with the 1994 Winter Olympic Games in Lillehammer. The report details the undertaking of a groundwater pollution vulnerability assessment of the Korgen waterworks. This assessment was based on a Digital Terrain Model, a MODFLOW groundwater flow model (both described in separate project reports) and a MODPATH particle tracking model. Potential pollution sources are listed together with an assessment of their potential effect on the waterworks. The groundwater sources for the waterworks are demonstrated and groundwater protection zones suggested.

Denne rapporten er utført som en del av NGUs bidrag til "Korgen vannverk"-prosjektet gjennomført av Berdal Strømme a.s.. Dette prosjektet utgjør en del av prosjektet ENSIS VANN som har sammenheng med 1994 Vinter OL på Lillehammer. Rapporten gir detaljer om arbeidet med en vurdering av forurensningssårbarhet ved Korgen vannverk. Denne vurderingen var basert på en Digital TerrengModell, en MODFLOW grunnvannsstrømningsmodell (begge beskrevet i egne prosjektrapporter) og en MODPATH partikkel-sporingsmodell. Potensioelle forurensningskilder er ført opp sammen med en vurdering av deres potensielle effekt på vannverket. Grunnvannskildene til vannverket er vist, og klausuleringsoner foreslått.

Keywords: hydrogeologi	grunnvannsmagasin	grunnvannsstrønming
forurensning	vannverk	fagrapport

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A GROUNDWATER VULNERABILITY ASSESSMENT OF THE KORGEN WATERWORKS, LILLEHAMMER KOMMUNE

1. INTRODUCTION

1.1 Project background

The Korgen waterworks is the principal water source for Lillehammer kommune. The waterworks are currently being upgraded to cope with increased demand during the Winter Olympic Games being staged at Lillehammer in February 1994. The upgrading is part of the ENSIS VANN project being carried out in close co-operation with Lillehammer kommune.

The groundwater vulnerability study described in this report forms the final part of the contribution of the Geological Survey of Norway to the ENSIS VANN project. This contribution included:

i) the collation of all existing data on the geology and hydrogeology of the Korgen and Hovemoen areas followed by the production of -
ii) a digital terrain model of the Korgen and Hovemoen areas,
iii) a groundwater flow model of the Korgen area and the southern part of Hovemoen and
iv) a groundwater vulnerability assessment of the Korgen waterworks.

Parts i), ii) and iii) are described in separate project reports.

This study examines the fate of pollutants after reaching the saturated zone; pollutant transport within the unsaturated zone has been considered in a separate part of the ENSIS project carried out by Jordforsk. The results of this study are detailed in Jonasson (1994).

It should be noted at this stage that the Korgen waterworks already has a high degree of protection from pollution. Groundwater protection zones in the form of land-use restrictions in the Korgen area were originally designated in 1973. For the E6 road passing to the north of Korgen, special measures have been taken to ensure that any spill or leakage from a road accident is contained and dealt with. In addition, there is a 'catastrophy plan' should an accident occur. This study is intended to demonstrate an alternative approach to assessing the vulnerability to groundwater pollution of the waterworks.

The location of the Korgen waterworks within the area of study is shown in Figure 1.

1.2 The objectives of the vulnerability study

The principal objectives of this study are to gain an overall understanding of the groundwater pollution risks to the Korgen waterworks through:

i) the development of an understanding of the groundwater flow systems in the Korgen area,
ii) the proposal of a protection zone scheme for the waterworks area,
iii) an assessment of the possible sources of pollution and
iv) an assessment of how these pollution sources would affect the waterworks should a pollution event occur.

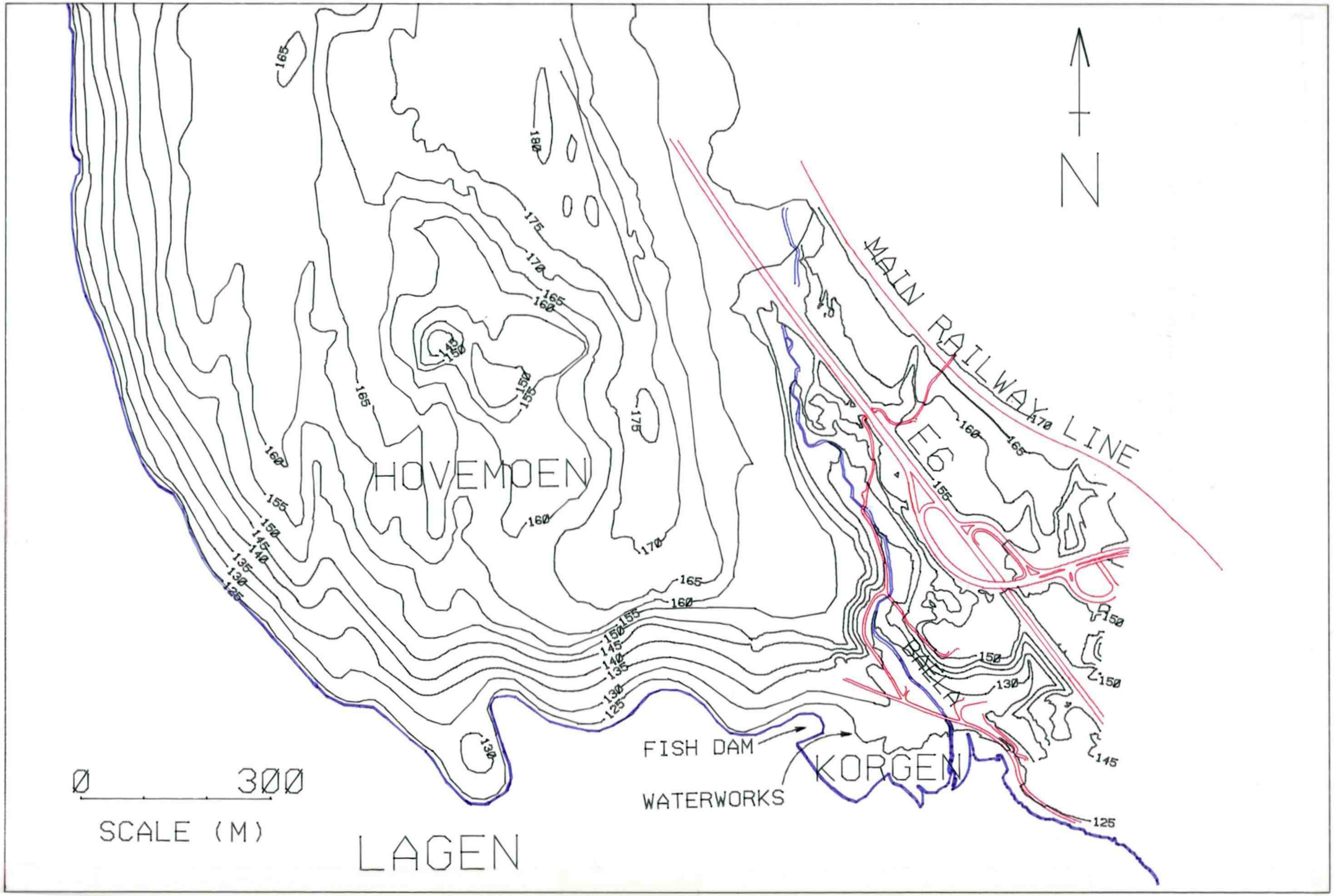

Figure 1. Location map of the study area showing the Korgen waterworks site on the Bæla fan.

1.3 Choice of method

Particle tracking techniques have been selected to evaluate the sensitivity of the Korgen area to groundwater pollution. Particle tracking techniques can be used to generate pathlines and time-of-travel information from numerical models and can be extremely useful in analysing complex two- and three-dimensional groundwater flow systems.

Particle tracking schemes have been incorporated directly into solute transport models to account for the advective component of transport. Particle tracking has also been used in "advection" models to generate pathlines and thereby provide a simple means of evaluating the advective transport characteristics of groundwater systems. One disadvantage of advection models is that they cannot be used to compute solute concentrations in groundwater because they do not account for the effect of mixing by dispersion. However, advection models represent a valuable intermediate step between groundwater flow models and advection-dispersion solute transport models. An advection model has therefore been chosen for this study.

Consequently, the fate of a conservative, non-reactive tracer is effectively considered in this study; no consideration is given as to how the type of pollutant will effect it's transport. The study therefore represents a 'worst case' situation as retardation, degradation and dilution, not considered here, will all lead to a lessening of the impact of a pollution event.

The model selected for the Korgen study is MODPATH which is an advection-only particle tracking model capable of calculating three-dimensional pathlines and positions of particles at specified times within a steady-state groundwater flow system.

MODPATH is executed as a post-processing package using output from steady-state simulations obtained with the U.S.Geological Survey modular three-dimensional finite-difference groundwater flow model, MODFLOW. The MODPATH model in this study therefore uses the output from the MODFLOW calibrated steady-state groundwater model of the Korgen area also produced as part of the ENSIS VANN project. This MODFLOW model is described in detail in an earlier project report. A summary is given in Section 2.1.

The MODPATH and MODFLOW models used in this study were both executed using Intergraphs' ERMA software package which provides a user-interface for the models and makes data preparation for the models both easier and faster. ERMA was executed on an Intergraph 20/20 Workstation loaned by Intergraph to NGU.

2. GROUNDWATER FLOW IN THE KORGEN AREA

2.1 The MODFLOW groundwater flow model

The MODFLOW groundwater flow model of the Korgen area produced earlier in the ENSIS VANN project enabled a good understanding of the groundwater flow processes occurring around the Korgen waterworks to be developed. In particular, it provided a single tool through which all the existing data and flow concepts could be tested. The results of this MODFLOW modelling are described in an earlier report. However, by applying MODPATH to the MODFLOW output, a much deeper understanding of the flow processes can be obtained particularly with regard to flow directions and rates.

The observed and modelled groundwater head distributions for the Korgen and Hovemoen areas are shown in Figure 2. This figure shows that the dominant direction of groundwater flow is SSW. The general pattern is considerably complicated by the presence of the Bæla stream which acts as a groundwater sink in it's upper reaches and as a weak groundwater source across the Bæla fan.

Three layers were used in the MODFLOW model to simulate the groundwater flow regime in the Korgen and Hovemoen areas. A brief description of these layers together with their hydrogeological properties is given below in Table 1.

Layer	Description	K_h (m/d)	K_v (m/d)	Θ_e
1	An upper, moderately high permeability layer representing the bimodal landslide deposit covering much of the western part of the Bæla fan. 0-20m thick.	20-500	1-10	0.18
2	An intermediate, very high permeability layer representing the main aquifer unit - the Bæla fan and associated deposits. 20-30m thick.	100-2000	10	0.18
3	A lower, low permeability layer representing the fine-grained deposits underlying much of the Korgen and Hovemoen areas. 40-80m thick.	0.004-0.01	0.004	0.18

Table 1. Hydrogeological units assumed for the Korgen and Hovemoen areas in the MODFLOW and MODPATH models (K_h and K_v - horizontal and vertical conductivity, Θ_e - effective porosity).

2.2 Groundwater sources

2.2.1 Method of determination

In order to trace the groundwater source or recharge areas for the Korgen abstraction boreholes, the reverse particle tracking facility of MODPATH was used. Here, particles in the wellfield area are tracked back to their point of recharge into the saturated part of the aquifer. The tracking assumes that Borehole No. 1 (the most northeasterly borehole) and Borehole No. 4 were pumping at rates of 150l/h and 100l/h respectively. These abstraction rates were used as they represent typical operating conditions. The fact that the boreholes are located so close together means that switching between abstraction boreholes is likely to make little difference to the local groundwater flow patterns or rates.

Particles were tracked from the wellfield to their source areas in Layers 2 and 3. Their travel times were also calculated. Layer 1 is absent from the wellfield area and so was not considered.

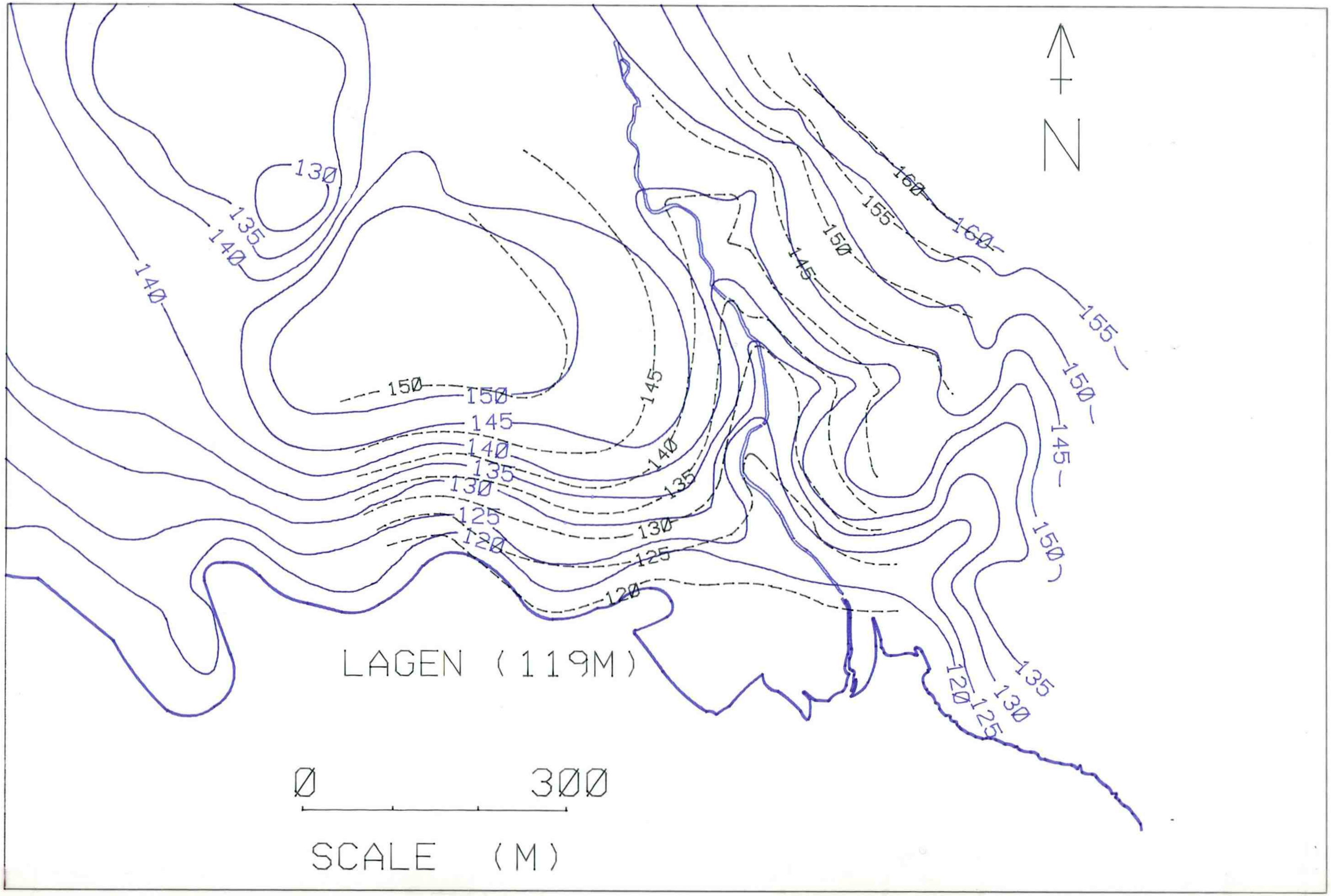

Figure 2. Observed and modelled groundwater head distributions (height above sea level, m). Solid blue line shows observed values (based on Østmo, 1972), dashed black line shows MODFLOW results.

2.2.2 The Bæla fan aquifer (Layer 2)

Figure 3 shows the tracking of particles from the wellfield area in the aquifer - Layer 2. This shows that a very high percentage of the groundwater comes from the Lågen to the west. In particular, the area of the fish dam to the northwest of the wellfield supplies a significant quantity of water to the wells. This is in agreement with tracer tests carried out on the aquifer by Dahl et al (1971). A small percentage of the water, approximately 5%, comes from infiltration through the bed of the Bæla stream. This value, however, is dependent on the permeability assigned for the bed of the stream itself. Unfortunately, little is known of this parameter.

The travel times to the wells are shown in Figure 4. This shows the very rapid groundwater transport occuring in the Bæla fan area, particularly to the northwest of the boreholes.

Travel times from the fish dam to the boreholes are approximately 5-10 days. Travel times from the Lågen in the west are of the order of 10-20 days. Lower flow rates occur in the southern part of the fan with travel times of approximately 50-55 days. These rapid travel times render the Korgen abstraction boreholes vulnerable to bacteriological pollution from the Lågen and, in particular, the fish dam.

Figures 3 and 4 show a small but significant source of groundwater from infiltration from the Bæla stream. Groundwater travel times from infiltration to the wells is approximately 10 days.

It is apparent from a study of Figure 3 that the groundwater abstracted from the Korgen wellfield is primarily derived from the Lågen with a minor contribution from infiltration through the bed of the Bæla stream. Some groundwater is also derived from vertical transfer of water from the underlying Layer 3. The groundwater derived in this way originates from the upland areas to the northwest and northeast of the wellfield. This source is considered in Section 2.2.3.

2.2.3 The lower fine-grained deposits (Layer 3)

Figure 5 shows the particle tracking diagram for the lower fine-grained deposits - Layer 3. This diagram shows the reverse tracking of particles in the Bæla fan area back to their recharge area. A number of points can be noted from this diagram.

The groundwater in Layer 3 flowing towards the Bæla fan area originates from two localised regions to the northwest and northeast of the fan area. Much of the groundwater recharged to the northwest flows directly into the Lågen. In addition, a significant percentage of the shallow groundwater in Layer 3 recharged within the Bæla catchment area will be intercepted by the stream. This implies that only a very restricted region acts as a groundwater recharge area for the Bæla fan. The groundwater in Layer 3 flowing towards the abstraction boreholes initially flows towards the fan area. As it reaches the area underlying the fan at depth it is diverted vertically upwards by the presence of a strong upward vertical gradient into Layer 2. Considerable dilution of this water is likely to occur before abstraction.

Groundwater flowing into the Bæla in the upper reaches of the stream may re-infiltrate the groundwater as the stream crosses the fan. Thus, the importance of ensuring that the bed of the Bæla stream is of low permeability can be seen. To assess the importance of this

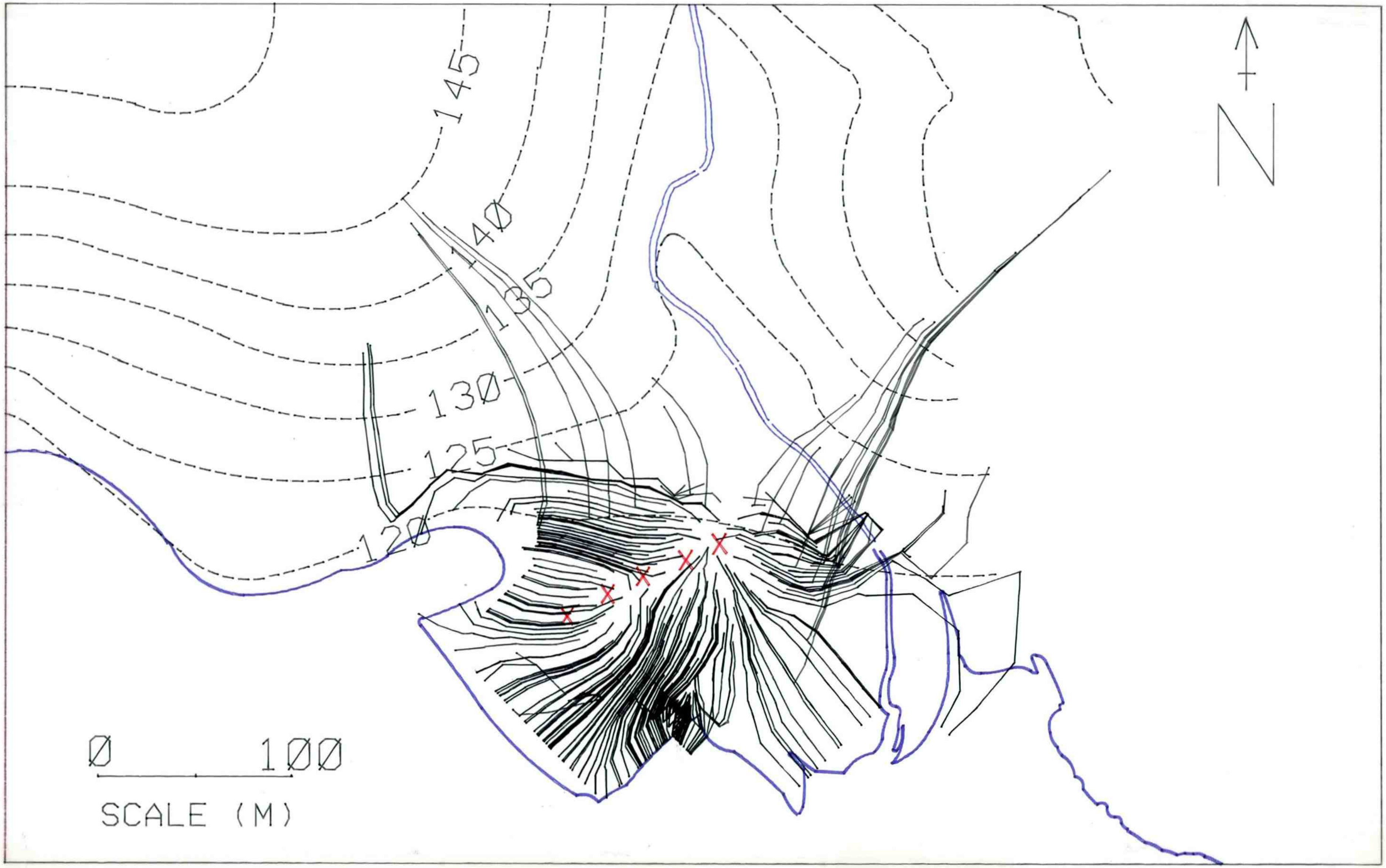

Figure 3. Pathlines for Layer 2 generated by reverse tracking of particles from the Korgen wellfield area to source. Abstraction borehole locations shown as red crosses. Dashed lines show modelled groundwater head distribution.

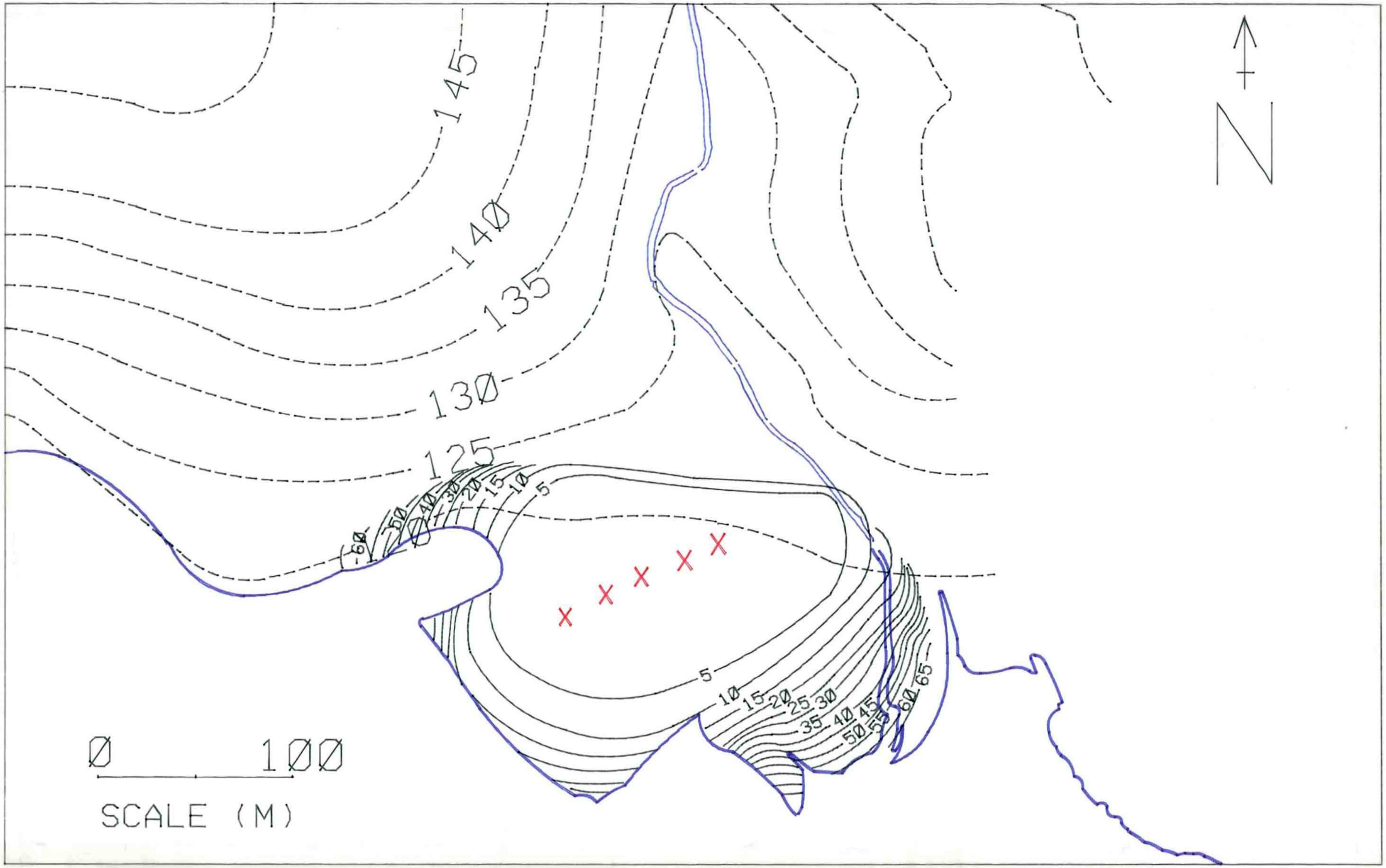

Figure 4. Travel times (in days) to the Korgen wellfield for the pathlines shown in Figure 3.

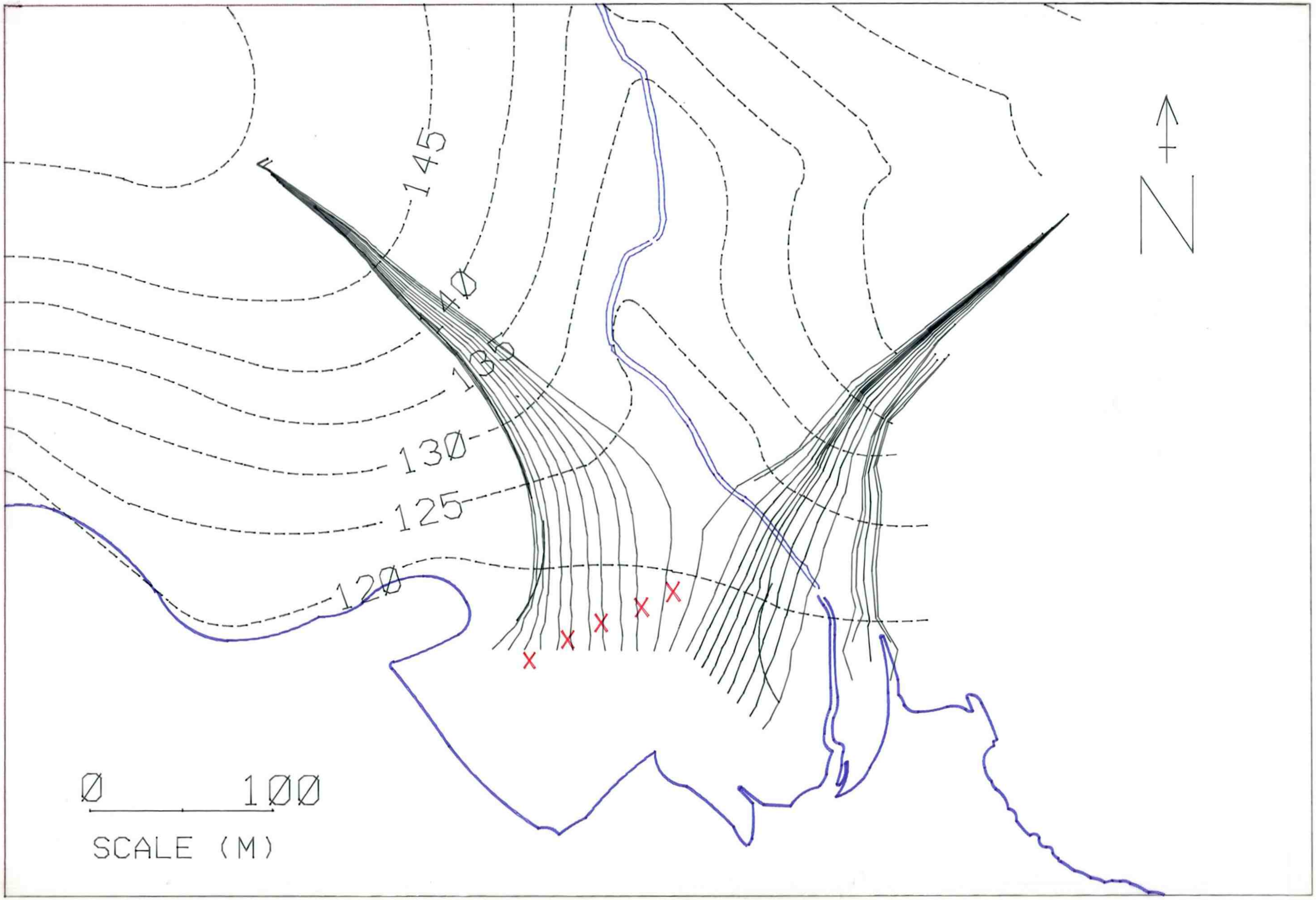

Figure 5. Pathlines for Layer 3 generated by reverse tracking of particles from the Korgen wellfield area to source.

process, further investigation would be required to determine the groundwater contribution to and from the Bæla. Given the low permeability of Layer 3 it is likely, however, that the groundwater contribution to the stream is low under 'normal' groundwater conditions i.e. when the upper high permeability layer is unsaturated.

An important aspect to consider when looking at potential pollution originating in Layer 3 is the travel time of any pollutant within the layer. The travel times for groundwater reaching the Bæla fan area in Layer 3 is shown in Figure 6. This shows the extremely long travel times from recharge to discharge of the groundwater in Layer 3. A typical total travel time is of the order of 1500 years. It should be noted that the "advective" model used here represents a worst case situation as adsorption, chemical reaction and dispersion are not taken into account in the model. These processes are likely to retard, dilute and attenuate any pollution plume particularly when travel times within the aquifer are large.

It should also be noted, however, that the terrain model assumes that the water table is approximately coincident with the interface between an upper coarse-grained layer and a lower fine-grained layer under 'normal' groundwater conditions. Thus, any increase in the groundwater level above this interface may result in rapid shallow groundwater flow. Furthermore, it is likely that this shallow flow will be intercepted by the Bæla stream and rapidly transported to the Bæla fan where re-infiltration may occur. This, again, highlights the importance of the Bæla stream and, in particular, the permeability of the stream bed in any potential pollution event.

3. POSSIBLE POLLUTION SOURCES AND THEIR POTENTIAL EFFECT

3.1 The potential sources

A survey of the potential pollution sources in the Korgen and Hovemoen areas identified the following possible sources:

- the Lågen and the fish dam
- the Bæla stream
- traffic accident on the E6 north or east of Korgen
- railway accident on the main railway line northeast of Korgen
- gravel extraction works in the Hovemoen area

3.2 The Lågen and the fish dam

Being the main water source for the Korgen abstraction boreholes, it is clear that the Lågen is potentially the biggest source of pollutants. Transit times from the Lågen to the boreholes are of the order of 5-20 days and consequently bacteriological as well as chemical pollution is a potential problem. The corollary of this is that any pollution event occuring as a result of pollution in the Lågen can be relatively quickly flushed from the aquifer as soon as the pollution in the Lågen is removed.

Infilling of the fish dam is now planned and this will improve the situation. However, it is clear from Figures 3 and 4 that bacteriological pollution from the Lågen will remain a potential threat even after the dam is filled in. The low groundwater travel times from the fish dam area to the

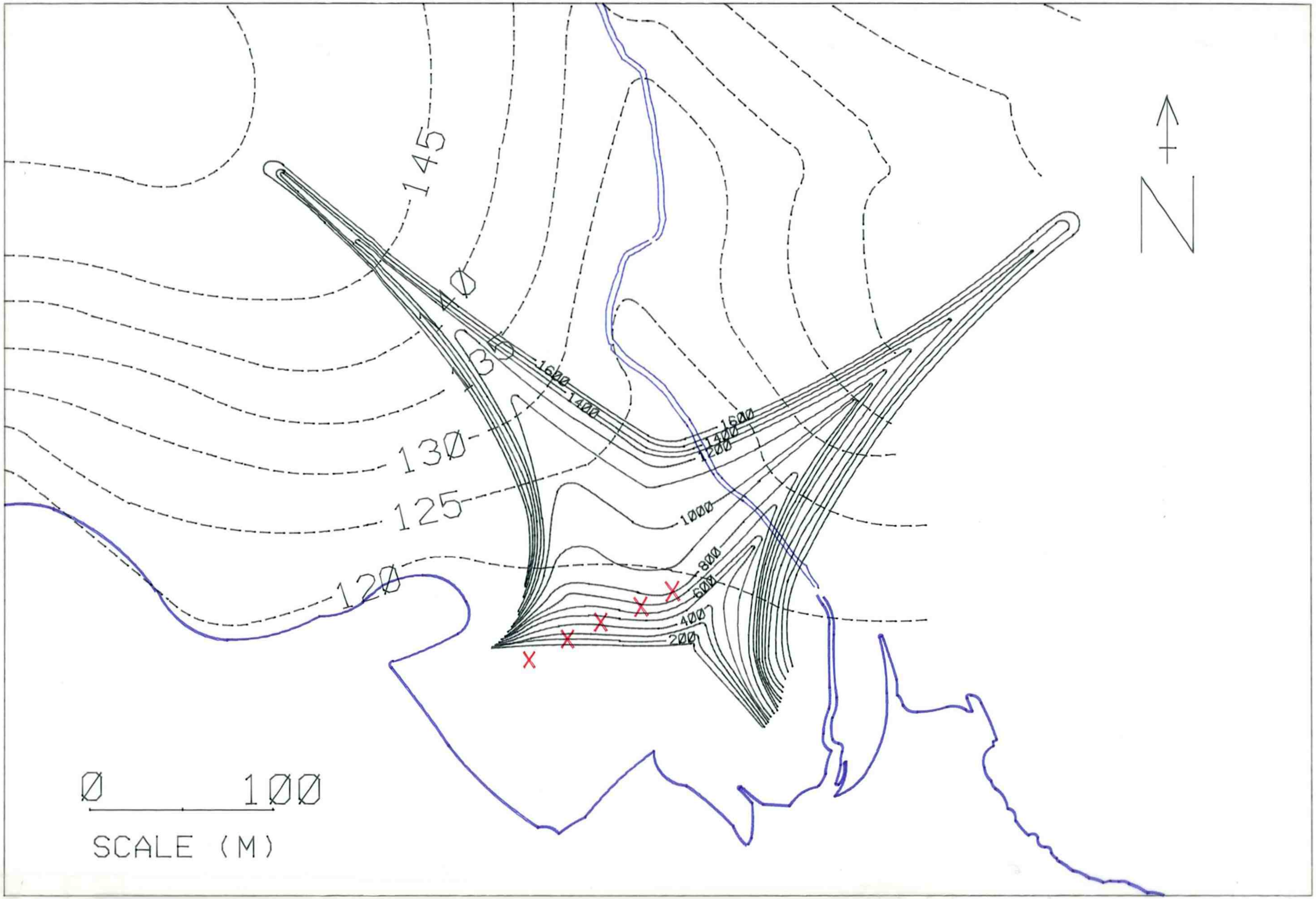

Figure 6. Travel times (in years) to the Korgen wellfield for the pathlines shown in Figure 5.

boreholes means that it is important to ensure that the material used to infill the dam is well-washed sand and gravel with a very low level of impurity.

3.3 The Bæla stream

The Bæla stream is capable of transporting polluted water originating within the entire surface water catchment area. Along much of the upstream length of the stream, the Bæla acts as a groundwater sink. However, where the stream crosses the Korgen fan area, it acts as a source. It is along this stretch of the stream that represents a potential pollution threat. Water infiltrated through the stream bed across the Bæla fan would be rapidly transported to the boreholes.

There is considerable uncertainty over the amount of infiltration occurring in this area. The MODFLOW model is of little use in determining this as the amount of infiltration is not a critical parameter in determining groundwater levels. However, it is likely that infiltration from the Bæla supplies approximately 5% of the total abstracted water. It is therefore a significant source and, whilst any polluted infiltrated water will be considerably diluted before reaching the wells, the importance of ensuring that the bed of the Bæla has a sufficiently low permeability to reduce infiltration can be seen.

During flood conditions, significant infiltration may occur should the Bæla stream overflow. However, dilution of any pollutants under these conditions would be considerable and would significantly reduce the pollution threat. Furthermore, the rapid groundwater transit times from the Bæla to the abstraction boreholes would enable a rapid flushing of the pollutants following cessation of the polluting event.

The role of the Bæla stream as a transport route for pollutants for specific pollutant events is further considered in Sections 3.4 and 3.5.

3.4 Traffic or railway accident

A traffic accident on the E6 road or a railway accident will produce similar sources - a pollution plume entering Layer 3 some distance north or northeast of the Korgen area. The MODPATH simulations have shown that, under 'normal' groundwater flow conditions, the rate of transport of any resulting plume within Layer 3 will travel extremely slowly, taking 1500 years or more to reach the wellfield. Furthermore, only pollution occuring in a very restricted area would reach the wells, as pollution occurring elsewhere will either flow to the Lågen or be intercepted by the Bæla.

However, as mentioned above, an increase in the groundwater level may result in rapid shallow groundwater flow occurring in the upper coarse-grained layer. As mentioned above, this shallow flow is likely to be intercepted by the Bæla stream and so the greatest pollution threat comes from re-infiltration of groundwater as the stream crosses the Bæla fan. This potential pollution threat is considered in Section 3.3.

3.5 Gravel extraction works in the Hovemoen area

Given the groundwater head map shown in Figure 3, it is highly unlikely that a pollution incident at the gravel extraction works in the Hovemoen area could influence the groundwater quality at

Korgen. The works lie on the other side of a groundwater divide from the waterworks and so any polluted groundwater would travel northwest.

There is some uncertainty over the accuracy of this map but, even given the absence of such a divide, it is clear from Figure 5 that much of the polluted water would either flow into the Lågen or be diverted into the Bæla. Unless the upper high permeability layer was saturated, as presumably occurs during times of high groundwater level, any polluted groundwater following the course from Hovemoen to Korgen shown on Figure 4 would take in excess of 1500 years and would also be considerably diluted and attenuated. Any groundwater travelling through a partially saturated upper high permeability layer would be subject to considerable dilution.

4. PROTECTION ZONES PROPOSAL

As a result of the study detailed above, groundwater protection zones are suggested. These zones are shown in Figure 7. The proposed zones have been constructed on the basis of the existing land-use restrictions. A consideration of these restrictions was outside the scope of the study. Three zones have been proposed, designated Zones I-III. The full extent of Zone III is not shown as it extends beyond the area covered by the terrain model. It is, however, identical to the Zone III currently in use.

Zone I is based on the 60 day travel time from the borehole recommended by the Norwegian State Institute for Public Health (SIFF). A similar definition is used in many groundwater protection zone schemes in Europe, notably Germany, Austria, Belgium and the Netherlands. This is based on the life expectancy of commonly occurring bacteria and is intended to protect the abstracted water from bacteriological pollution. It is clear from particle tracking analysis that a complete protection is not possible because of the short transit times from the Lågen to the boreholes. A sub-zone, Zone Ia is designated to include the immediate vicinity of the boreholes and is primarily intended to ensure protection of the waterworks site itself.

Zone II is designated on the basis of the groundwater recharge area supplying the Bæla fan area, including the Korgen waterworks. This recharge area has been determined through particle tracking analysis. It thus represents the approximate limit of origin of the groundwater flowing to the Bæla fan area.

Zone III is designated as the surface water catchment area and thus represents the limit of all surface water flowing to the fan area. It has been designated to include the Hovemoen area as there is some uncertainty concerning the geology and hydrogeology of this area.

The zones are essentially similar to the existing zones and generally support the work completed to date. However, the current work has highlighted the potential importance of infiltration of polluted water from the Bæla stream and the vulnerability of the Korgen waterworks to pollution in the Lågen.

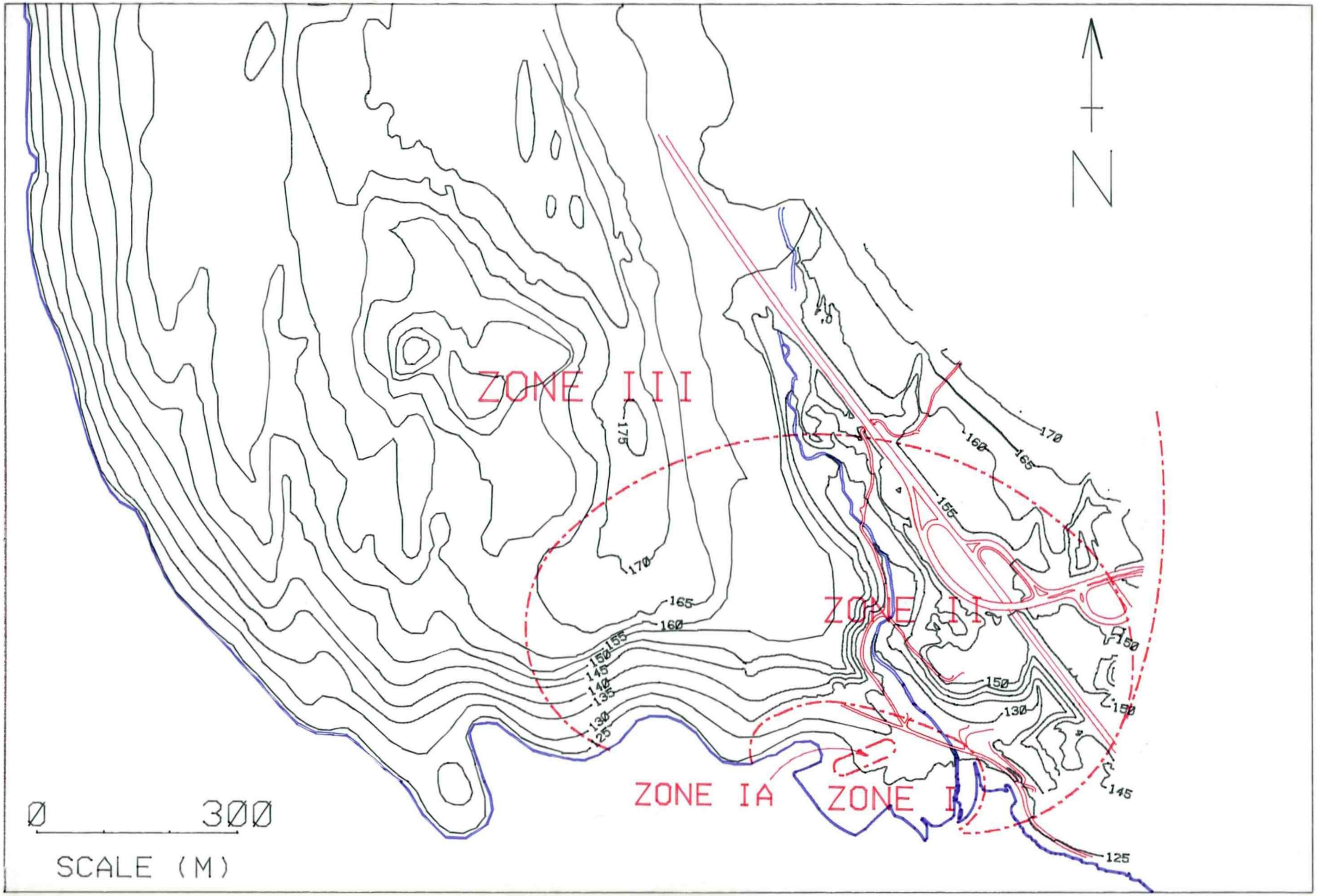

Figure 7. Suggested groundwater protection zones for the Korgen wellfield.

5. UNCERTAINTIES AND LIMITATIONS

There are essentially two types of limitations to be considered in any groundwater modelling study - the limitations due to the underlying assumptions of the method used and the limitations due to uncertainty in parameters and boundary conditions.

Probably the most important limitation due to the method involved concerns the discretization. The degree of spatial discretization in a finite-difference model influences the level of detail at which the hydrogeological conditions and, in particular, boundaries can be represented. It also influences the accuracy of the velocity calculations, particularly in an area close to a wellfield.

The most important limitation of any groundwater analysis is, however, the uncertainty in the boundary conditions and hydrogeological parameters used to define the system. Models are always idealized approximations of reality. A numerical model provides information about how water moves in the idealized system described by the model.

As with any groundwater model, the accuracy of the MODFLOW and MODPATH models presented in this study can be no more accurate than the data from which it is produced. The terrain model used in the production of the MODFLOW model is considered to be generally accurate. However, it contains an important but, as yet, untested assumption that, across the area outside the immediate Korgen area, the groundwater table coincides with an interface between upper coarse-grained and lower fine-grained sediments. The assumption is based principally on the work of Soldal (1988) although other workers, such as Østmo (1972), have also come to the same conclusion.

A 'worst case' situation is that the water table is actually higher than the interface. This would permit the transport of considerably larger quantities of pollutants in the upper high permeability layer. However, there are two factors which would reduce the impact of such a situation. Firstly, much of the water which drains from the higher areas to the north and east of Korgen drains either to the Lågen or is intercepted by the Bæla stream. Only a very restricted recharge zone supplies the Korgen fan area from these areas. The second factor is that significant dilution of any pollutant plume is likely to occur before reaching the boreholes as Layer 3 provides only a small fraction of the total water abstracted.

The permeability estimates used in the calibration of the MODFLOW model were derived from grain size analyses and pumping test in the Korgen area. With the exception of one data point in the central Hovemoen area, no data were available outside the area of the Bæla fan. Significanmt errors may result in the calculated travel times should the permeability estimates produced from the calibration not be representative. In addition, no recharge estimates were available for the area.

These uncertainties must be borne in mind when considering the results of this study.

6. CONCLUSIONS

1) A steady-state MODFLOW and MODPATH model has been produced which has successfully simulated the groundwater flow system in the Korgen and southern Hovemoen areas. The model was calibrated against the groundwater head distribution produced by Østmo (1972). The MODPATH model used for the study is an advection-only model and therefore represents a 'worst-case' scenario as all dilution, attenuation and retardation of pollutants are ignored. The results of the MODFLOW and MODPATH models have provided an insight into the groundwater flow processes occurring in the Korgen and Hovemoen areas.

2) The studies have shown that the dominant source of groundwater for the Korgen abstraction boreholes is the Lågen. In particular, the area to the northwest of the boreholes including the fish dam supplies the greatest quantity of water. The aquifer is of extremely high permeability with values of up to 2000m/d being interpreted from the MODFLOW model. Such high permeability values result in very high groundwater transport rates and would enable the aquifer to be rapidly flushed following a pollution event. This has been considered with respect to specific potential pollution events.

3) Infiltration from the Bæla is a secondary source of water for the abstraction boreholes, providing approximately 5-10% of the total water abstracted. The permeability of the bed of the Bæla is clearly critical in determining the quantity of water infiltrating. However, little is known of this parameter.

4) Under 'normal' or low groundwater conditions little water is derived from the areas to the north or east of Korgen. During high groundwater level conditions, the upper high permeability layer may become partially saturated, creating a shallow high velocity pathway for groundwater. Much of this shallow groundwater, however, will either drain directly into the Lågen or be intercepted by the Bæla stream. Dilution of the groundwater will also considerably reduce the impact of any pollution event occurring in these areas.

5) Five main potential pollution sources were identified in the Korgen and Hovemoen areas:

- the Lågen and the fish dam
- the Bæla stream
- traffic accident on the E6
- railway accident
- gravel extraction works in the Hovemoen area

6) Travel times from the Lågen and the fish dam are very short, being in the order of 5-20 days. Bacteriological as well as chemical pollution is therefore a potential problem. However, a corollary of this is that rapid flushing of any pollutants would be possible on removal of the pollutants from the Lågen. Removal of the fish dam will improve the situation but it is clear that bacteriological pollution will remain a potential threat. It is important to ensure that the material used to infill the dam is well-washed sand and gravel with a very low level of impurities.

7) The Bæla stream is capable of transporting pollutants from within it's entire surface water catchment zone. Where the stream crosses the Bæla fan, infiltration of polluted water may occur and flow to the abstraction boreholes. Whilst considerable dilution of any pollutants would occur

en route to the boreholes, it is important to ensure that infiltration from the Bæla across the area of the fan is minimised. Even with such measures, infiltration may occur under flood conditions should the Bæla flood. Dilution of any pollutants under such conditions would, to some extent, reduce the pollution impact.

8) A road traffic or railway accident would both result in the introduction to the groundwater of a pollutant plume to the north or east of Korgen. Under 'normal' or low groundwater conditions groundwater transport rates from these areas are extremely low. The MODPATH simulations suggest that it would take in excess of 1500 years to reach the boreholes. During high groundwater levels, however, the partially saturated high permeability layer may provide a shallow higher velocity pathway for pollutants. As noted above, however, this flow is likely to be either intercepted by the Bæla or to flow directly into the Lågen.

9) Groundwater protection zones have been suggested which broadly agree with the zones currently in use. Three zones have been suggested, designated Zones I-III. Zone I is defined by the 60 day groundwater travel zone to the well. This suggested zone is slightly larger than the current Zone I and represents the most vulnerable part of the aquifer. Zone II is the recharge area for groundwater flowing to the Bæla fan area. Zone III is the surface water catchment area. The land use restrictions applying in these proposed Zones I-III are assumed to be identical the current restrictions.

10) A number of uncertainties exist which could be reduced with further study. Little hydrogeological information is available outside the immediate area of the boreholes. Groundwater levels and permeability estimates from the lower fine-grained layer in the northern and eastern parts of the study area would greatly reduce the degree of uncertainty. Measurement of the elevation of the groundwater table outside the wellfield area would also help in determing whether the assumption of a coincident groundwater table and fine/coarse sediment interface is valid.

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