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**Onderwerp:** Waterbalans coupépolder

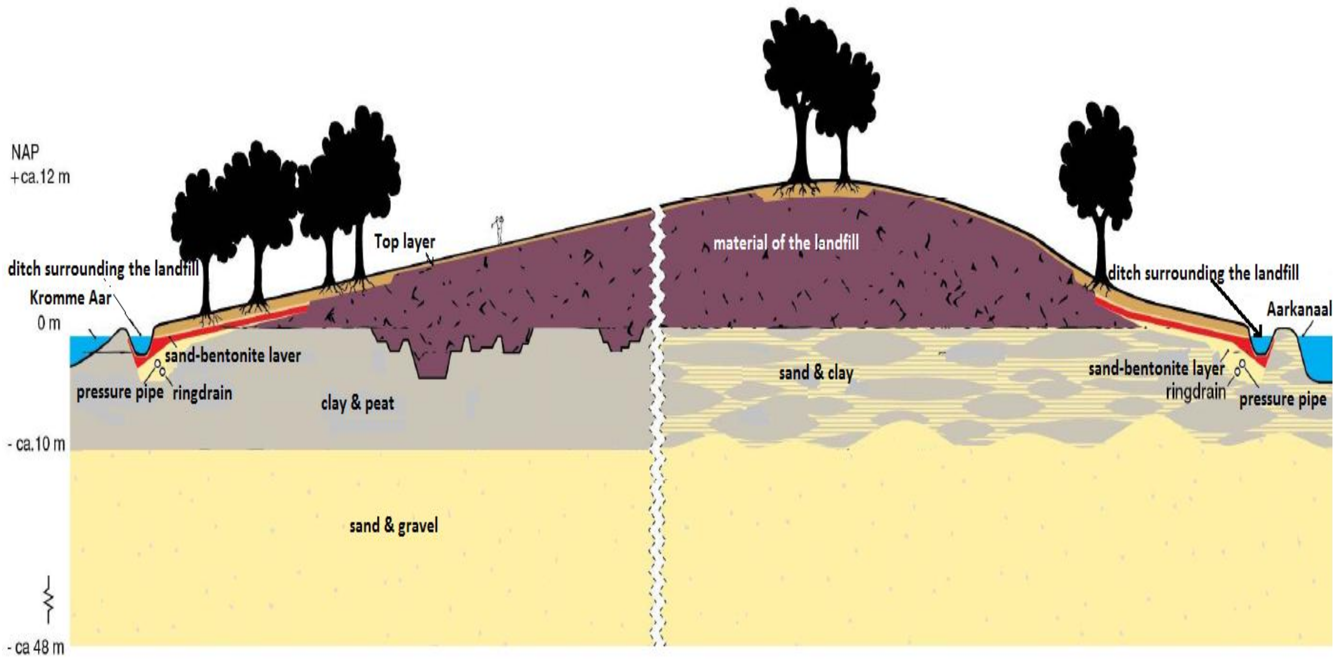
Beste meneer Bosselaar,

Hierbij mijn scriptie. Ik hoop dat de mail deze keer wel aankomt en dat de datalimiet niet wordt overschreden.

Met vriendeljke groet,

Hans van Hateren

# A revised water balance of landfill 'de Coupépolder' and recommendations for future data improvement.




Adapted from H. Eijsackers, M. Prins, T. Edelman, 2012.

*Bachelor's thesis,*
*Hans van Hateren,*
*2507136,*
*25-6-2014*

## Abstract

Landfill 'de Coupépolder' lies northeast of Alphen aan den Rijn. There are concerns that toxic fluids leak from the landfill to the underlying aquifer because the landfill is partly underlain by permeable sediments of a channel fill. It is therefore important to determine whether the flux between the landfill and the aquifer is directed downward or upward. This study aimed to resolve this question by setting up a revised water balance. Earlier water balances of TNO (1980) and Iwaco (1985) took place when the hydrological system was still very different from the current situation. The sides of the landfill have since been capped with bentonite clays, decreasing the amount of infiltration (Promeco, 2002). Furthermore, the vegetation has changed from grass and clover (Iwaco, 1985) to grass, shrubs and trees, altering the amount of evapotranspiration. Moreover, a drain has been added under the sides of the landfill. What also lacks in these studies is the contribution of golf club Zeegersloot to the hydrological system: shallow drainage and irrigation of the golf course. A more up to date study of Royal Haskoning (2006) lacks irrigation, uses an approximation in the type of vegetation for evapotranspiration and does not give an error estimate to fortify the calculation. Apart from a revised water balance with uncertainty range, this study aimed to propose the most cost-effective method to improve future data. The current outcome of the water balance is an upward seepage of $2{,}4 * 10^4$ m3/year. To compare this flux to the amount of precipitation, it can be divided by the total area of the landfill. This gives an upward seepage of 107 mm/year, compared to 844mm precipitation (in reality, the seepage will only take place through the sandy channel fill, or approximately 1/3 of the area). With a matlab script developed for this study, the amount of error could be calculated. The outcome was that even for a 95 percent confidence range, the flux cannot be said to be upward: the upper boundary of the 95 percent confidence range is an infiltration of 2740 m3/year. It is therefore interesting to know which options are available to improve future data. This study provides a method for error reduction for every flux used in the water balance. The methods were tested through the same matlab script used for estimating the current error. Their benefits in error reduction of the outcome of the water balance were compared to their cost to propose the most cost-effective method. The proposed method is to install an automatic rain gauge in situ. This method lowers error in the amount of precipitation by removing the error due to spatial variation. The benefit of this method is that the result of the water balance can be said to be an upward seepage for a 99 percent confidence range. The method costs €1.000 in initial costs plus a recurring yearly cost of €650 for one decade, making the total cost €7.500.

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# 1. Introduction

The Netherlands, being a densely populated country, has frequent problems with groundwater pollution. Where polluted groundwater resurfaces, it can harm people who come into direct contact with it, or it can pollute aquifers used either for irrigation purposes or for drinking water. In the western part of the Netherlands, one of the major sources of groundwater pollution are landfills. Landfills usually overlie a clayey or other impermeable subsurface. No subsurface, however, is truly impermeable. Therefore, every landfill is prone to leakage. If leakage occurs, the most important factors to be reckoned with are the toxicity of the fluids in the landfill and their ability to be moved by groundwater flow. One well-known Dutch example of a landfill that partly overlies a relatively permeable subsurface and that also contains toxic chemicals is the Coupépolder (H. Eijsackers, M. Prins, T. Edelman, 2012).This landfill is of special concern because it is underlain by a sandy channel fill, which greatly increases the likelihood of seepage. Furthermore, there is evidence that heavier toxins were illegally dumped in the landfill, increasing the potential ecological damage and the potential damage to public health.

Multiple attempts have been carried out to determine whether the flux between landfill and first aquifer is downward or upward. The first water balance stems from TNO 1980, calculating an infiltration of 135 mm/year with an error of 59 percent (TNO, 1990)(Municipality Alphen aan den Rijn, 2007). The second water balance stems from Iwaco, 1985, calculating an infiltration of 120 mm per year. These water balances are now outdated because the sides of the landfill have since been capped with bentonite clays, decreasing infiltration rates (Promeco, 2002). Furthermore, the vegetation has changed from grass and clover (Iwaco, 1985) to grass, shrubs and trees, altering the amount of evapotranspiration. Finally, a drain has been added under the sides of the landfill (a ring drain). These studies also lack an assessment of the impact of golf club Zeegersloot caused by shallow drainage and irrigation of the golf course. In contrast to earlier studies, Royal Haskoning (2006) calculated an upward seepage from the first aquifer towards the landfill with a value of 181 mm/year. This study was a significant improvement over previous assessments since it took into account the ring drain as well as drains in the top-layer put in place by the golf club. It also allowed for horizontal flow of groundwater from outside the area towards the ring drain (the hydraulic head of the ring drain is lower than the water level in the canals around the area). However, not all factors have been properly incorporated. Firstly, the golf club irrigates the green in summer, which possibly provides an extra input to the system (K. van Hateren, 2014). Secondly, no uncertainty range is given for the outcome, which makes it hard to judge its validity and robustness. Thirdly, the evaporation value was calculated using a vegetation consisting exclusively of grass: This assumption is questionable since a substantial part of the area has been planted with trees and shrubs and a smaller part of the area is unvegetated (fig. 1). Finally, a misinterpretation of technological drawings of the sides of the landfill led to a significant overestimation of the flux from outside the landfill towards the ring drain. Hence, the present study aimed to calculate a more accurate value for infiltration to or upward seepage from the first aquifer, as well as to include an uncertainty range. To this end, a new water balance was created introducing irrigation and a revised value for evaporation and allowing for the uncertainty in the datasets.


Figure 1. The surface of the landfill consists of grass, trees and unvegetated areas. Adapted from: Google Earth, Aerodata International Surveys, 2014)

In addition to providing an improved water balance, this study set out to propose the most cost-effective method for reducing error in the outcome of future water balances. Due to large errors in datasets of the different inputs and outputs, the current outcome of the water balance is ambiguous. It is, therefore, interesting to examine possibilities for error reduction in the datasets. Different methods were proposed and for each the cost was estimated. The amount of error reduction in the outcome of the water balance (the benefit), was calculated using a matlab script developed during this research. Thus, the most cost-effective method could be selected.

## 2. History and (geo)hydrology of the Coupépolder

The Coupépolder is located northeast of Alphen aan den Rijn and is bound by the Kromme Aar and the Aar canal (fig.2). It originally belonged to the Zuid- and Noordeinderpolder but was cut off when a canal was dug to straighten the Kromme Aar (Coupepolder.nl). The initial small-scale garbage dumping began in 1934. In 1972, the entire area became designated as landfill. In subsequent years, a waste management company bribed the gateman and dumped toxic waste from factories and hospitals (K. van Hateren, 2014). This illegal dumping has never been administrated and thus the exact quantity and toxicity of this material is unknown. By 1985, the landfill was completely filled. It was then covered with a protective cover soil and turned into a golf course for golf club Zeegersloot (Coupepolder.nl).

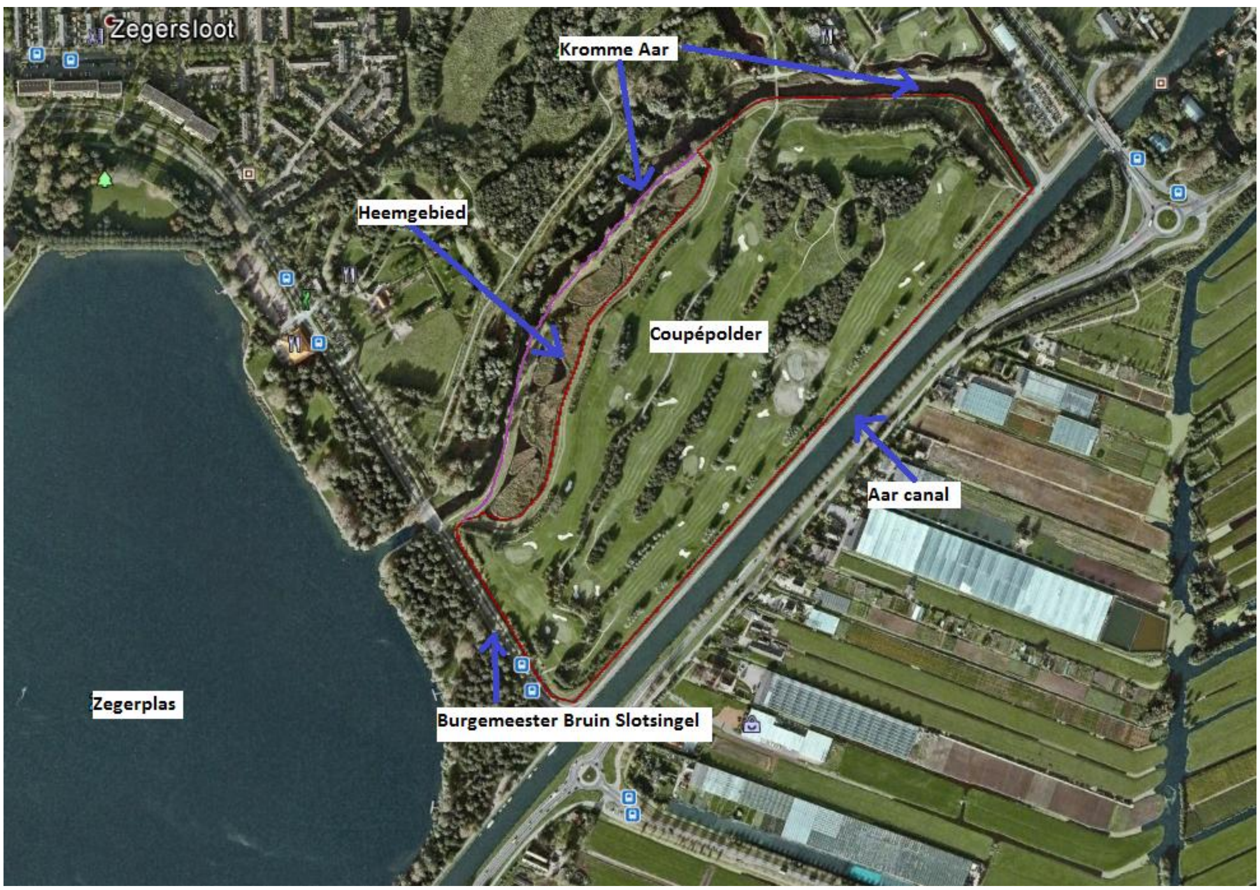

Figure 2. The Coupépolder with surrounding features. Adapted from: Google Earth, Aerodata International Surveys, 2014).

It is the geological situation under the landfill that causes concern (fig. 3). The landfill is underlain by 10 m of Holocene sediments, of which the clastic sediments belong to the Naaldwijk formation and the peats belong to the Nieuwkoop formation (Dinoloket.nl, 2014). This formation, in turn, is underlain by the first aquifer, consisting of sandy deposits of the formations of Boxtel (previously named Twente formation) and Kreftenheye (appendix 5),(Iwaco, 1992). Underlying the first aquifer are Rhine sediments of the Waalre formation, consisting of clays and fine sands (previously named Kedichem formation). Since these sediments have a high resistance and the hydraulic head difference between the first and

the second aquifer is small, this layer is seen as the lower boundary of the hydrological system of the landfill.
The sediments underlying the landfill are early Holocene clays of the Calais phase (Naaldwijk formation) and the basal peat (Nieuwkoop formation) (Dinoloket.nl). In an undisturbed stratification, these sediments act as a seal due to their high hydraulic resistance (± 30.000 days (Iwaco,1988)). However, the northern part of the landfill is underlain by a late Holocene sandy channel-fill of the Kromme Aar (Iwaco, 1988), which is part of the Duinkerke phase. This paleochannel has eroded most of the older Holocene deposits. The channel-fill has a much lower resistance (±5000 days or less (Iwaco, 1988)) and could therefore facilitate leakage to the underlying aquifer. Consequently, it is important to determine the interaction with the first aquifer: Is there a net downward or a net upward flux?

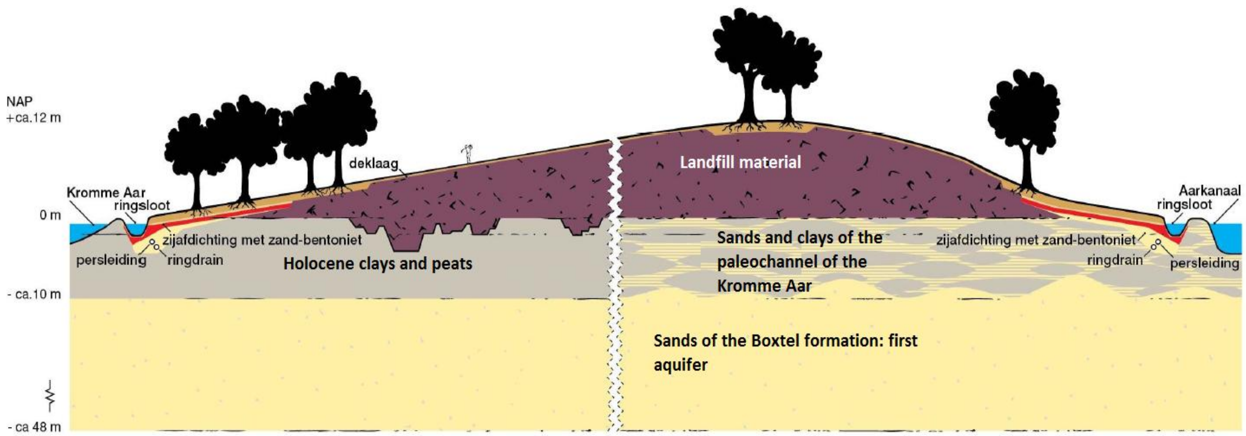

Figure 3. Geology under the landfill. Adapted from H. Eijsackers, M. Prins, T. Edelman, 2012.

Due to the vast costs associated with soil remediation of a landfill of 22 hectares it was decided to monitor and drain the area in perpetuity. Hence, the hydrological system of the landfill became a complex interaction between artificial and natural fluxes. There are three types of water in the hydrological system of the landfill: uncontaminated runoff and shallow groundwater in the top soil (shown in figure 4), uncontaminated groundwater in the first aquifer and in the area outside the landfill and finally water that has percolated through the landfill and that is therefore contaminated. Wherever possible, contaminated water is prevented from mixing with uncontaminated water. The top of the landfill was covered with a topsoil for the plants to root in. This measure prevents the plants from coming into contact with the landfill itself. The sides of the landfill were capped with an impermeable sand-bentonite layer. This layer continues under the ditch that surrounds the landfill (fig. 4). Hence, it forms a barrier between clean water (groundwater in the toplayer and runoff) and contaminated water in the landfill. As a result, water from the ditch can safely be released into the Kromme Aar (appendix 6). Five percent of the topsoil is drained by shallow drainage and this flux of clean water is added to the ditch(appendix 8). The water level in the ditch is controlled by overflows and inlets that connect it to the Kromme Aar (appendix 6).

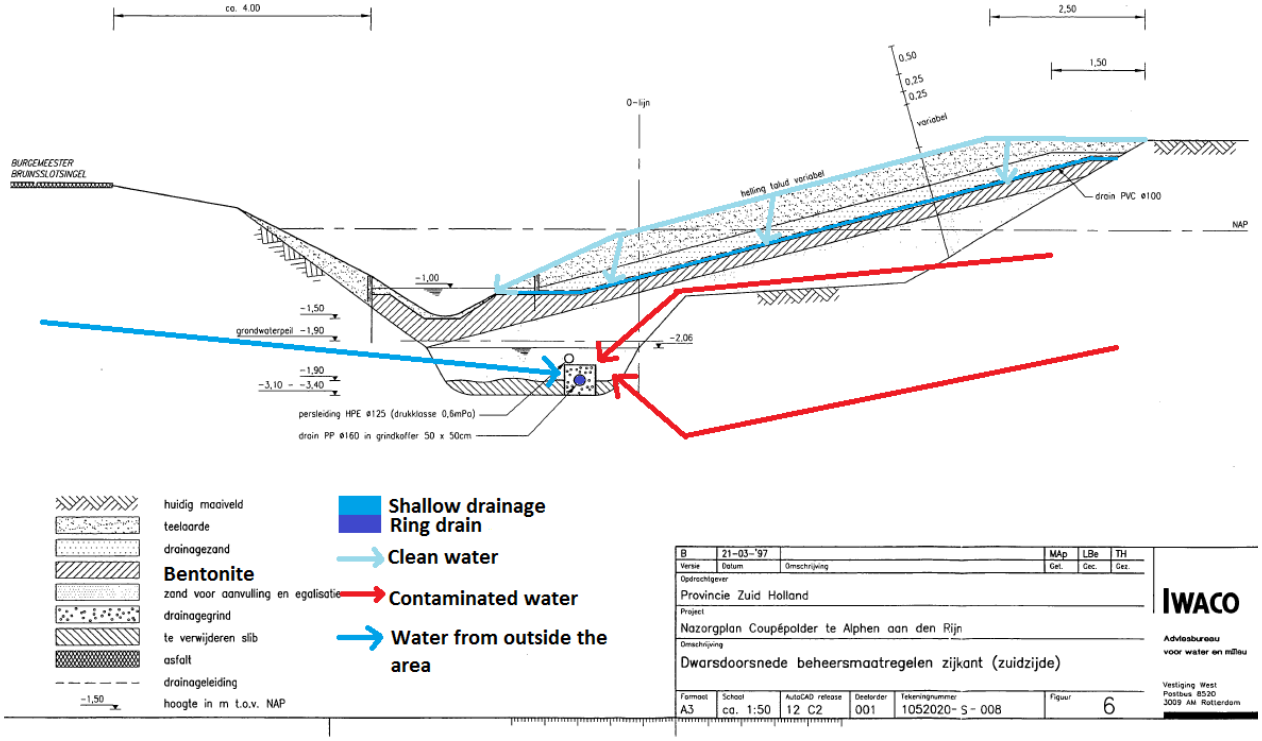


Figure 4. Sand bentonite layer, drainage measures and resulting fluxes.

Because the landfill has not been sealed off at the top, it still receives an input of precipitation. The precipitation surplus percolates through the landfill and becomes contaminated. This water has to be prevented from leaving the landfill sideways through the Holocene. Therefore, a ring drain was installed around the area, lowering the hydraulic head at the sides of the landfill. This drain receives percolation fluids from the landfill, groundwater from outside the area and possibly groundwater from the first aquifer (fig. 4). Its large outflux makes it is an important factor in the water balance. There are three pumping stations for this drain: pumping station Kromme Aar (north side), pumping station Aarkanaal (east side) and pumping station Heemgebied (west side). The outlets of these three station are fed into the main pumping station, which in turn pumps the contaminated water to the municipal sewer system (appendix 7). Subsequently, the water is cleaned at the water treatment plant of Alphen aan den Rijn. A side-effect of the drain is that it also attracts a flux from outside the landfill, through the Holocene. For simplicity, this flux will be called the flux from side to ring drain in the remainder of the article. The last flux is the interaction between the landfill and the first aquifer. The natural and artificial fluxes distinguished in this study are shown in figure 5.

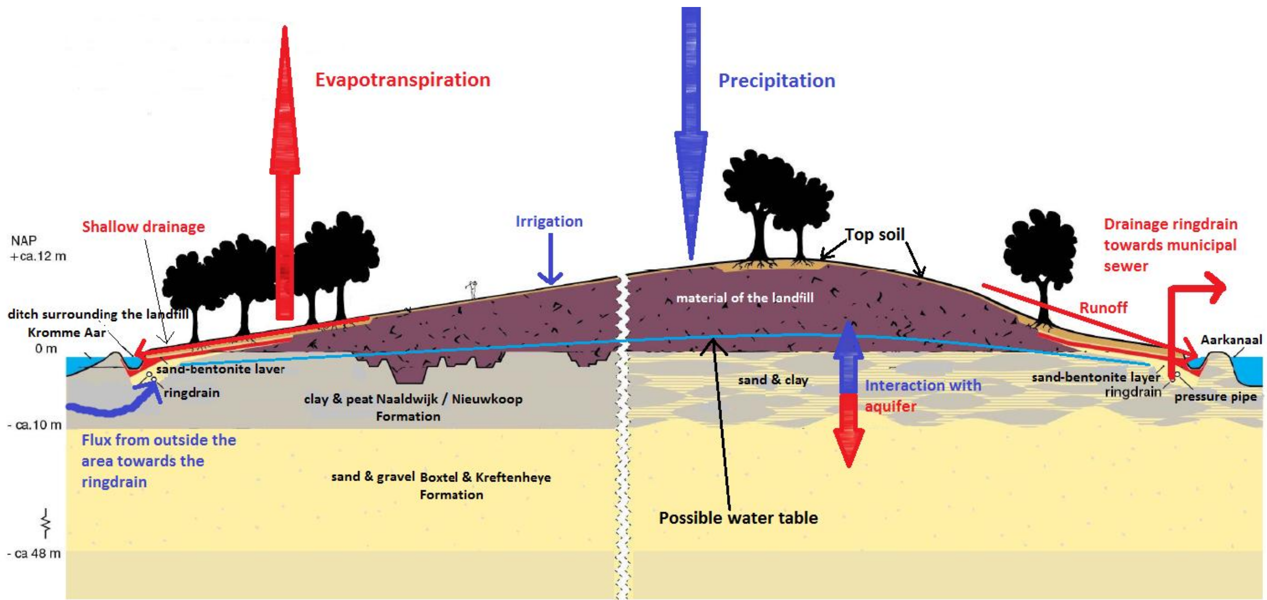

Figure 5. Sketch of the hydrological system of landfill the Coupépolder. Adapted from H. Eijsackers, M. Prins, T. Edelman, 2012.

# 3. Data and method

## 3.1 Fluxes used in the water balance

To calculate the flux (interaction) between the landfill and the underlying aquifer a water balance was used. In this water balance the landfill was seen as a black box which is fed by certain fluxes of water and from which other fluxes debouch. Over multiple years the total flux into the landfill was assumed to be in equilibrium with the total flux out of the landfill. Fluxes into the landfill consist of rainfall, irrigation and a flux from the area around the landfill towards the ring drain. Fluxes from the landfill consist of evapotranspiration, discharge of the ring drain (deep drainage) and discharge of the shallow drains. The interaction with the aquifer is the closing term in this water balance and can either be an influx or outflux (appendix 2).

Precipitation
The climatic mean annual precipitation was calculated for the last 30 years (1984-2013). Data were obtained from weather station Schiphol. At this station the climatic mean annual rainfall is 844 mm/year ( KNMI, 2014). To calculate the flux in cubic meters, it was multiplied by the surface over which it contributes to the hydrologic system of the landfill. This is, however, not the entire surface of the landfill: the sides of the landfill were capped with an impermeable sand-bentonite layer. The function of this layer is to prevent percolation fluids from the landfill to flow to the ditch encircling the landfill. Along 500 m of the Kromme Aar this layer is 25 m wide (Royal Haskoning, 2006, appendix 3). The other sides (1700 m) have a sand-bentonite layer of 10 m width. Thus, the total area underlain by the sand-bentonite layer is 29500m2. A side effect of this layer is that the rainfall over this part is deflected to the canal around the landfill. Therefore, the acreage that is underlain by the sand-bentonite layer can be seen as if it were decoupled from the hydrological system of the landfill.

Flux from side to ring drain
After precipitation, the flux from side to ring drain is the largest input. The flux was calculated using a formula derived from the original formula of Darcy (H. Darcy, 1856):

$$Q = k * D * \Delta h / \Delta x * L * J$$

In which:
Q = the yearly groundwater flux in cubic metres
K= the horizontal permeability in m/day (in this case the horizontal permeability since there is large anisotropy in Holocene);
D = the thickness of the phreatic aquifer in m (amount of vertical space for groundwater flow);
Δh = the difference in hydraulic head between the Holocene and the ring drain in m;
Δx = the horizontal distance towards the ring drain in m;
L = the length in m of a specific section parallel to the landfill;
J = the number of days in a year (on average 365,25).

The yearly flux was calculated separately for four sides of the landfill because they have different values for Δh, Δx and D (fig. 6)

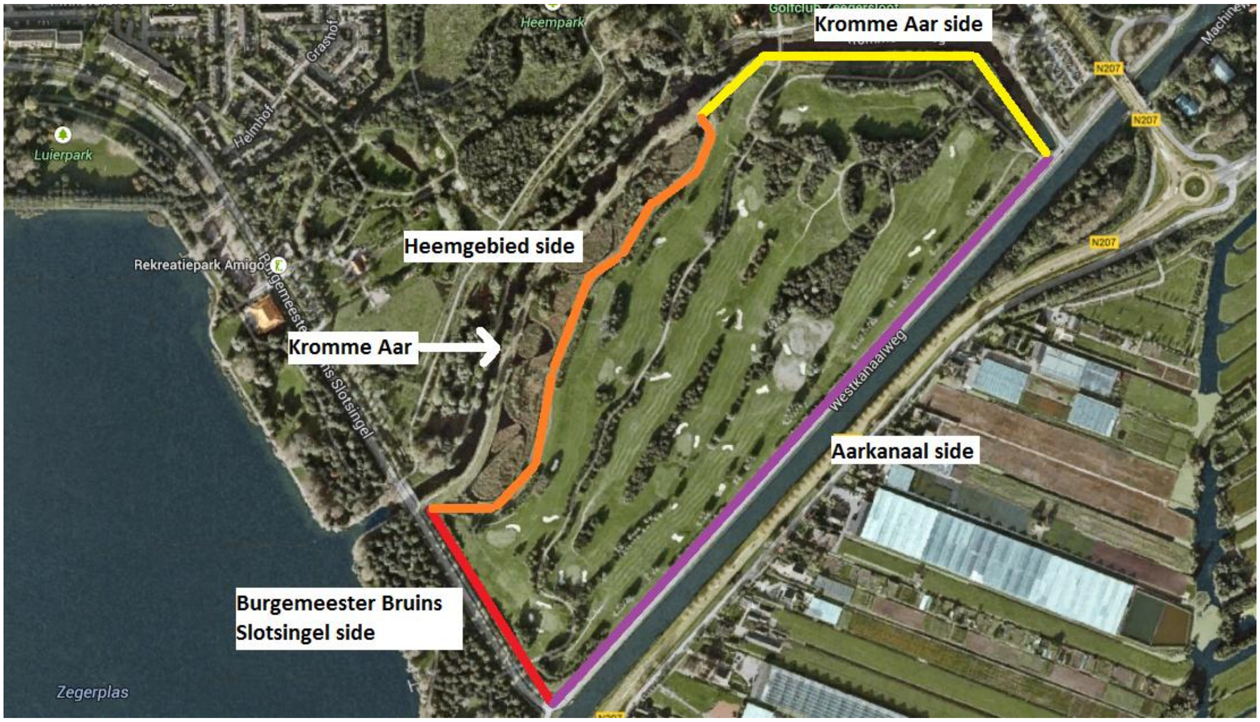


Figure 6. Sides of the landfill with different parameters in the Darcy calculation.

The main problem with calculating this flux is the uncertainty in hydraulic parameters of the Holocene. The horizontal permeability of the Holocene (khor) was estimated at 0,01 meter/day by Royal Haskoning, 2006. Rijnland estimates kver at 0,002-0,004 m/d. With a maximal anisotropy (factor 10) the khor is 0,02-0,04 m/d. Since Royal Haskoning later admitted that the khor might be larger, this study used a khor of 0,03 (municipality Alphen aan den Rijn, 2007).
The permeability along the Kromme Aar was set to zero because the dam along this side was built to prevent groundwater flow towards the ring drain. The variables D, Δx and L were taken from the water balance of Royal Haskoning, 2006). Δh was calculated as the difference between the hydraulic head of the groundwater around the drain and the water level of the source.
The thickness of the phreatic aquifer is 10 m. However, along the side of the Heemgebied there are two types of groundwater flow. One originates from the Heemgebied, the other from the Kromme Aar (fig. 6). These two flows were calculated separately by estimating that the flow from the Heemgebied (Heemgebied 1) passes through the upper 5 m of the Holocene and the flow from the Kromme Aar (Heemgebied 2) passes through the lower 5 m (Royal Haskoning, 2006).
A mean hydraulic head near the ring drain was calculated for each side. Subsequently, this height was subtracted from the water level of the source of the flux (the nearest open water) to get Δx. Data for the mean hydraulic head were taken from 18 monitoring wells placed in the flanks of the landfill (appendix 3).

The wells were allocated in this manner:
Heemgebied: well 11, 12, 13, 15 and 16.
Aarkanaal: well 2 through to 6.
Kromme Aar: well 7 through to 10 plus 17 and 18.
Burgemeester Bruin Slotsingel: well 1 and 14.
Since the hydraulic heads did not vary much between different years, the means were calculated for 2010 and 2011 (Bodemzorg, 2011).

Irrigation
At the time of data-acquisition the amount of irrigation was not yet measured properly. However, some rough estimates were given by the greenkeeper of golf club Zeegersloot (L. Van Reeuwijk, 2014). The total amount of water used in a dry period was estimated at approximately 130 m3. The greens are only irrigated if the humidity of the soil in which the grass roots is below 18 percent. Each parcel of grass is irrigated for a maximum of ten minutes. Noting the small amounts of water given each time, in combination with the low humidity of the top soil when irrigation takes place, it seems likely that all irrigated water is used by the grass and none is passed on to the underlying landfill. Thus, the irrigation flux was set to zero in the water balance.

Evapotranspiration
Evapotranspiration is the largest outflux to be reckoned with. Precipition and evapotranspiration together make up the precipitation surplus. KNMI Schiphol daily radiation measurements started in 1988 and, since then, daily values for Makkink evapotranspiration have been calculated. The daily values used in this study stem from 28-01-1988 to 27-01-2014. Since 1987, KNMI uses the Makkink equation to calculate evapotranspiration. This is an empirical relationship defined by Gerrit Francois Makkink (KNMI, 2014) which expresses evapotranspiration as dependent on the amount of radiation and temperature. This equation was developed specifically for a well-watered grass surface in a temperate climate. It takes the following form:

$$ET = 0{,}61 * \Delta/(\Delta + \gamma) * \mathrm{Rs}/\lambda - 0{,}12$$

Where:
Δ= the slope of saturation vapour pressure curve (in mb/◦C);
γ = the psychrometric constant (in mb/◦C);
Rs = the total solar radiation in $cal*cm^{-2}*day^{-1}$;
λ= latent heat of vaporization, 2.45, MJ $kg^{-1}$
(C.Y. Xu and V. P. Singh, 2002)

The Makkink evapotranspiration formula calculates a reference evapotranspiration over a well-watered short cropped grass surface with cool-weather grass species. To compensate for differences in interception and transpiration rates between different plant species crop factors can be used.
As the area is used as a golf course, the vegetation consists predominantly of short cropped cool-weather grass with a crop factor 1. The remaining area has been planted with trees, mainly maple and poplar. Deciduous trees intercept precipitation and consequently their evaporation rate increases.

Therefore, reference evapotranspiration of the deciduous trees was multiplied by a factor 1,17 during the growing season, when the trees are fully leafed (M.J. Waterloo, 2014). To approximate the area that is dominated by grass and the area that is dominated by different tree species, Google Earth was used (Google Earth, Aerodata Internation Surveys, 2014)(appendix 11). This program features a polygon drawing tool which will automatically calculate the area under the polygon. Subsequently, the vegetation areas were converted to percentages of the total area.

From the daily reference makkink data and the cropfactor data a climatic mean Makkink evapotranspiration was calculated in two steps:

1. $$daily\ ET = \ daily\ ETref * ((Ctrees * \%trees) + (Cgrass * \%grass))$$

2. $$mean\ ET\ = \frac{Daily\ ET}{n} * 1 * 10^{-3}\ * J\ *\ surface\ \ ET$$

In which:
daily ET = daily Makkink evapotranspiration in mm, from 28-01-1988 to 27-01-2014.
daily ETref = daily Makkink evapotranspiration in mm, from 28-01-1988 to 27-01-2014 (Royal Meteorological Institute of the Netherlands, 2014).
Ctrees = cropfactor of trees, 1 in winter, 1,17 in growing season (M.J. Waterloo, 2014). Vector with daily values.
%trees = percentage of total area dominated by trees.
Cgrass = cropfactor of grass, 1 year round. Grass of the golf course is seen as similar to the reference crop: A well watered, short clipped, cool-weather grass species.
%grass = percentage of total area dominated by grass.
mean ET = climatic mean yearly evapotranspiration in m3.
n = number of days between 28-01-1988 and 27-01-2014.
Factor $1 * 10^{-3}$ is used to convert from mm to m.
J = mean number of days in a year (365,25).
Surface ET = the total area of the landfill minus the area underlain by the sand-bentonite layer in m2. (The sand-bentonite layer is decoupled from the top of the hydrological system of the Coupépolder).
See also: appendix 1a, fluxes out, evapotranspiration.

Ring drain
After evapotranspiration, the ring drain contributes most to the outflux. This drain was installed in 1993 to prevent contaminated groundwater from seeping out of the flanks of the landfill. (H. Eijsackers, M. Prins, T. Edelman, 2012). Total yearly fluxes per station were collected in yearly maintenance reports from 1996 to 2011(Promeco, 1997-2004),(Bodemzorg, 2005-2012).

Shallow drainage
The shallow drainage makes a minor contribution to the outflux. As with irrigation, its flux has not been measured properly. The discharge of these drains had to be estimated from two estimated figures: The

area they drain and the amount of water they drain per square meter per year. The area drained was estimated from a map with the locations of the drains (appendix 8). This area was measured on the map. This area was then multiplied by the precipitation surplus.

## 3.2 Water balance with uncertainty range

The water balance itself is a simple calculation: the total influx consists of precipitation, a groundwater flux towards the landfill and from the area around the landfill, and irrigation (set to zero). The total outflux consists of evapotranspiration, deep drainage by the ring drain and shallow drainage. Subtracting the two gives the remaining flux: the interaction between landfill and aquifer.

Standard deviation
To make the outcome of this study more robust, an estimation of error was essential. Therefore, the standard deviation of every flux had to be estimated. Firstly, for each an error percentage was estimated. This error percentage was taken to be equal to a 95 percent confidence range. Since this range equals 1,96 standard deviations to either side, the standard deviation could be calculated using the following simple formula:
$STDEV = Mean * (\frac{error\%}{100})/1{,}96$

Matlab script
The mean of the variable, together with its standard deviation was led through a Matlab script developed for this study (appendix 1). All inputs of the script are summarized in table 1 at the end of this subchapter. Firstly, a variable and its standard deviation were led through a pseudorandom number generator. The pseudorandom number generator took the mean and standard deviation of a flux as input. The desired amount of iterations can be specified and for this study it was set at $1 * 10^8$, since this number of iterations gave a smooth curve of normally distributed results. Thus, a vector with $1 * 10^8$ possible values was created. This procedure was followed for every variable. Secondly, the vectors of the outfluxes were subtracted from the vectors of the influxes. This calculation led to a vector with possible results for the closing term of the water balance. Lastly, the normal distribution was plotted and the 95- and 99 percent confidence intervals were calculated.

Precipitation
The error in the climatic mean precipitation is twofold: Firstly, an error is derived from the measuring equipment. For an automatic rain gauge the error lies around 7,5 percent (M.J. Waterloo, 2014). Secondly, there is an error derived from the spatial variation in climatic mean rainfall. The Coupépolder lies approximately 20 km south of weather station Schiphol. Due to spatial variation the data obtain an estimated extra 7,5 percent error, leading to a total of 15 percent error (appendix 10),(M.J. Waterloo, 2014).

Flux from side to ring drain
The error in the estimate for the flux from side to ring drain mainly lies with hydraulic parameters of the Holocene sediments. As mentioned earlier, the horizontal permeability of the Holocene (khor) was

estimated to be 0,01 meter/day by Royal Haskoning 2006. Rijnland estimates khor at 0,02-0,04 m/d. Using these values, the flux ranges from 4.600 m3/year to 20.000 m3/year (municipality Alphen aan den Rijn, 2007). From these earlier estimates, the possible error was calculated: (20.000+4.600)/2= 12.300. (12.300-4.600)/12.300=0,63, or approximately 60 percent.

Irrigation

Since the amount of infiltration of irrigation water was argued to be zero, the error was also set to zero. If an error were to be introduced in the matlab script, it would be an unilateral error: infiltration cannot be an outflux.

Evapotranspiration

The error in evapotranspiration data from KNMI station Schiphol was estimated at 7,5 percent (M.J. Waterloo, 2014). The main variable dictating spatial variation of yearly evapotranspiration is the climatological mean radiation pattern (fig. 7). A line drawn from Schiphol to the Coupépolder is approximately parallel to the radiation pattern. Thus, Schiphol and the Coupépolder receive approximately the same amount of climatological mean radiation and therefore have approximately the same amount of reference evapotranspiration. Thus, it is likely that there is no further error associated with spatial variation.

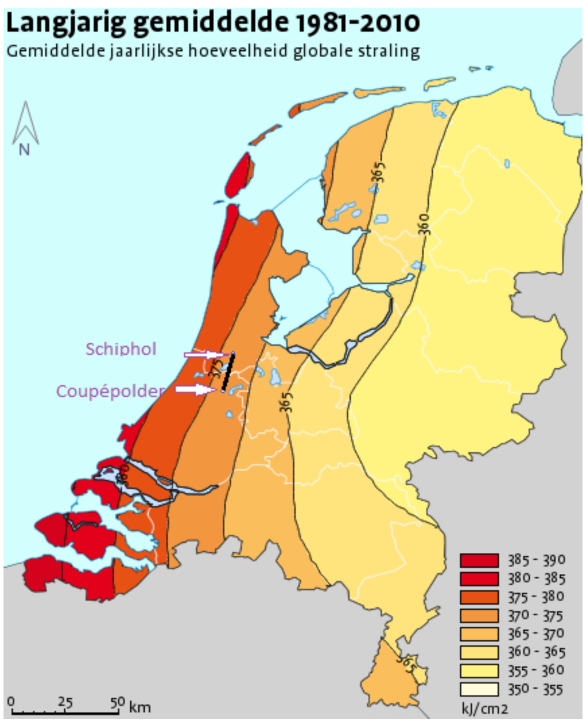

Figure 7. Isohyetal lines of climatological mean radiation. Adapted from KNMI.nl

Ring drain

The three pumping stations of the ring drain are equipped with doppler flowmeters. These flowmeters are very sensitive, reliable and have an error range of only 5 percent (M.J. Waterloo, 2014).

Shallow drainage

The shallow drainage, on the other hand, comes with a far greater error.  It is not equipped with any measuring device. Thus, the flux had to be estimated from the area drained and the precipitation surplus. Since the precipitation surplus is the maximum amount that can be drained, this calculation has an unilateral error (only negative). The error was estimated at 100 percent unilaterally. The unilateral error was simulated in two steps: Firstly, the error range was implemented bilaterally in the same manner as with the other fluxes. Secondly, all values higher than the mean were converted to the mean value (appendix 1b).

Table 1. inputs of the matlab script for error calculation.

| | Mean (m3/year) | Error in % for 95 % confidence range | Standard deviation (m3/year) | Error in % with method | Standard deviation (m3/year) |
|---|---|---|---|---|---|
| Precipitation | 1,6284*10^5 | 15,0 | 1,22*10^4 | 7,5 | 6,11*10^3 |
| Side to ring drain | 7,5793*10^3 | 60,0 | 2,32*10^3 | 20,0 | 7,73*10^2 |
| Irrigation | 0 | 0,0 | 0 | - | - |
| Evapotranspiration | 1,1706*10^5 | 7,5 | 4,48*10^3 | - | - |
| Ringdrainage | 7,4792*10^4 | 5,0 | 1,91*10^3 | - | - |
| Shallow drainage | 2,3387*10^3 | -100 (unilateral) | 1,19*10^3 | 5,0 | 5,97*10^1 |

## 3.3 Methods for future error reduction

For every variable a method was selected to reduce the amount of error. The amount of error reduction in the result of the water balance was tested by entering the new standard deviation into the same matlab script as used in chapter 2.2. Furthermore, the cost of each method was estimated by the initial cost of installation and the yearly recurring cost of working hours and maintenance. For methods that should produce a mean yearly value, it was estimated that at least a decade of measurements is needed. Therefore, yearly recurring costs were summed over this period to produce the total cost.

Precipitation

The error in precipitation data is twofold: instrumental error and spatial variation.  The method proposed here is to install a rain gauge in situ, thus avoiding all spatial variation. With correct usage and proper regular maintenance of a rain guage, the error in precipitation data can be reduced by 7,5 percent. An automatic rain gauge costs approximately €1000 and needs only 15 minutes of cleaning per week (M.J. Waterloo, 2014). This might performed by an employee of golfclub Zeegersloot at approximately €50 per hour (€12,50 per week). The data can be collected and stored by Wareco. There are no extra costs associated with the data collection since Wareco is under contract to monitor the landfill.

Flux from side to ring drain

Since error in this flux mainly lies with the horizontal permeability, a possible improvement would be to conduct a geological research around the sides of the landfill to measure this parameter. In contrast to the well known vertical permeameters, horizontal permeameters are still in development. In a study of

B. Smith & D. Bloomquist, 2010, a prototype horizontal permeameter yielded promising results. However, costs and possible error of the apparatus were not mentioned. The permeameter would have to be assembled and tested. Since it is small (approximately 15x15x15 cm) and consists of cheap materials as tubes, stainless steel bolts, porous Genpore® plastic and plexiglas, material costs will be low (B. Smith & D. Bloomquist, 2010). However, assembling and testing the apparatus until satisfactory results are acquired will be time-consuming and therefore expensive in personnel costs. An estimate of the cost would be: 3 full time weeks for assembly and testing (3*40h*€50/h=€6.000, €500 material costs, 1 full time week for the research (40h*€50=€2.000), €500 for additional costs during research. Together, this amounts to €9.000. If ten samples were taken around the landfill a resolution of 220 m would be achieved (cirumference/number of samples =2,2km/10=220 m (afstandmeten.nl, 2014)). Due to horizontal variation in the sediments, the remaining error in horizontal permeability would be relatively high. The minimum remaining error was estimated at 20 percent.

Irrigation

The amount of irrigation seeping through the top soil into the landfill is zero or very small. Thus, installing an expensive flowmeter will not be cost-effective. A second option would be to ask the greenkeeper of golf club Zeegersloot to note down information regarding the irrigation: pumping hours of the irrigation pump, date and time of irrigation and the duration of irrigation at one spot (to verify if the top layer was saturated enough to start leaking). Although less expensive than the first measure in the short term, this would mean a lot of extra work for the greenkeeper, as well as extra work for Wareco to interpret all the data. In fact, even with data covering every irrigation event, it will still be up to expert judgement to decide whether there is any through flow, leaving us with only a slight improvement over our starting point. Since the flux of irrigation is small or even zero, this method would provide an insignificant improvement in error.

Evapotranspiration

In contrast to irrigation, evapotranspiration is a large flux, for which even a slight improvement in certainty would be beneficial to the certainty in the outcome. To measure evapotranspiration in situ a weather station is needed. This weather station should measure temperature, relative humidity, radiation and wind speed. Such a station would cost around 2.500 us dollars (1850 euro)(http://www.scientificsales.com). However, differences between Schiphol and the Coupépolder due to spatial variation are minor. Radiation, the most important factor for spatial variation of evapotranspiration, is approximately the same at the two locations. Wind speed is another important factor in evapotranspiration. Since both locations are approximately at the same distance from the coast and their surface resistance is approximately equal (both mainly grass), windspeed will not differ much between them.

Deep drainage

As mentioned in chapter 2.2, the current doppler-flowmeters that measure the flux of the ring drain have a high accuracy. They have an error of approximately 5 percent. Thus, the most effective measuring device has already been installed.

Shallow drainage

To improve data on shallow drainage, a simple, yet costly solution would be to install flowmeters at each drain outlet. This would lower the error to approximately 5 percent (M.J. Waterloo, 2014). As depicted in appendix 8, there are 6 outlets. A doppler-flowmeter costs around 1800 U.S. dollars (€1350) (Omega.com, 2014), making the total cost of the measuring devices €8100. There would probably be around €2.000 extra in working hours and machinery costs, making the total cost around €10.000. Aggregating the 5 outlets on the south side would bring the cost for flowmeters down to €2700. However, the costs of this construction, including the pump that would be needed, would probably end up in the same range as the cost of separate outlets.

# 4. Results

In this chapter the results of the water balance and the benefits of the proposed methods will be discussed. Firstly, the mean flux of the interaction between the landfill and the first aquifer will be discussed and compared to the waterbalance of Royal Haskoning 2006. Secondly, the calculated error in the current situation will be presented. Lastly, the results of the cost-benefit study of methods for reducing error will be presented. 99 Percent confidence ranges are shown for each method. They are compared to the amount of uncertainty in the current situation to determine the benefit. To complete the cost-benefit analysis, these results are compared to the cost of each method. In conclusion, the most cost-effective method is proposed.

## 4.1. Result of the water balance

Precipitation
Mean yearly rainfall (0,8438m) was multiplied by the infiltration area (total area - area underlain by sand-bentonite layer) (for further calculations, see chapter 2.1).

$$Flux\ rainfall\ =\ 0{,}8438m * (222.440 - 29.500)m2 = 1{,}628 * 10^5 m3$$

Flux from side to ringdrain
The flux from side to ring drain was calculated using the formula of Darcy, 1856:

$$Q =\ k * D * \Delta h/\Delta x * L * J$$

Results are shown in table 2.

table 2. variables and parameters in calculation of flux from side to ring drain in m3. a: water level Heemgebied. b: water level Kromme Aar. c: water level Aarkanaal. d: water level Zegerplas.

| | k | D | water level | Hydraulic head near ring drain | Δh | Δx | L | Q |
|---|---|---|---|---|---|---|---|---|
| Heemgebied 1 | 0,03 | 5 | -1,7 (a) | -1,91 | 0,21 | 15 | 600 | 460 |
| Heemgebied 2 | 0,03 | 5 | -0,6 (b) | -1,91 | 1,31 | 50 | 600 | 861 |
| Aarkanaal | 0,03 | 10 | -0,6 (c) | -2,28 | 1,68 | 25 | 800 | 5891 |
| Kromme Aar | 0 | 10 | -0,6 (b) | -1,89 | 1,29 | 5 | 500 | 0,00 |
| Burg. Bruin Slotsingel | 0,03 | 10 | -0,6 (d) | -1,94 | 1,34 | 100 | 250 | 367 |
| Total | | | | | | | | 7,579* 10^3 |

Irrigation
Irrigation was kept at zero, as argued in chapter 2.1 and by Royal Haskoning (2006).

Evapotranspiration

Using matlab, evapotranspiration was calculated from daily Makkink reference evapotranspiration from KNMI Weather station Schiphol. The result was a climatic mean yearly evapotranspiration of 1,1706*10^5 m3, or 613 mm.

Ring drain

The mean yearly flux of the ring drain was calculated from yearly data. Table 3 shows the gathered data and the resulting mean.

Table 3.Yearly fluxes in m3 for the three pumping stations, with percentage of total flux between brackets. source: Yearly maintenance report Coupépolder, 1996- 2011 (Jaarverslag beheer Coupépolder).

| | Pumping station Aarkanaal | Pumping station Kromme Aar | Pumping station Heemgebied | Total |
|---|---|---|---|---|
| 1996 | 18.299 (55%) | 6.415 (19%) | 8.373 (25%) | 33.087 |
| 1997 | 24.738 (60%) | 7.669 (18%) | 9.063 (22%) | 41.470 |
| 1998 | 64.417 (60%) | 18.568 (17%) | 25.181 (23%) | 108.166 |
| 1999 | 54.796 (58%) | 18.458 (19%) | 21.633 (23%) | 94.887 |
| 2000 | 56.625 (61%) | 18.012(19%) | 21.084 (20%) | 95.721 |
| 2001 | 57.331 (56%) | 19.475 (19%) | 24.980 (25%) | 101.786 |
| 2002 | 45.566 (58%) | 16.617 (21%) | 17.512 (22%) | 79.695 |
| 2003 | 33.379 (55%) | 13.654 (22%) | 13.772 (23%) | 60.805 |
| 2004 | 36.396 (53%) | 16.174 (24%) | 16.134 (23%) | 68.704 |
| 2005 | 37.532 (55%) | 14.189 (21%) | 16.325 (24%) | 68.046 |
| 2006 | 40.199 (56%) | 15.914 (22%) | 16.071 (22%) | 72.184 |
| 2007 | 47.719 (54%) | 18.399 (21%) | 21.527 (25%) | 87.645 |
| 2008 | 43.366 (57%) | 15.218 (20%) | 17.603 (23%) | 76.187 |
| 2009 | 36.914 (59%) | 13.024 (21%) | 12.828 (20%) | 62.766 |
| 2010 | 43.608 (55%) | 18.166 (23%) | 18.129 (23%) | 79.903 |
| 2011 | 38.533 (59%) | 12.935 (20%) | 14.159 (22%) | 65.627 |
| Total | 679.418 | 242.887 | 274.374 | 1.196.679 |
| Mean yearly flux | 42.464 | 15.180 | 17.148 | 7,479*10^4 |

Shallow drainage

The total drained area is approximately 10.133 m2 (5 percent of the total area). This figure was multiplied by the yearly precipitation surplus to get an estimate of the yearly flux: 10133 m2*(0,844-0,613 m/year)= 2.339 m3/year.

water balance

The resulting water balance of landfill 'the Coupépolder is:

Table 4. Water balance of the Coupépolder.

| Flux | Amount ($*10^4$ m3) |
|---|---|
| Precipitation | 16,28 |
| Flux from side to ringdrain | 0,76 |
| Irrigation | 0,00 |
| Evapotranspiration | -11,71 |
| Ringdrainage | -7,48 |
| Shallow drainage | -0,23 |
| Interaction with aquifer | -2,38 |

To counterbalance this deficit in the water balance, there has to be an influx, or upward seepage from the first aquifer to the landfill of 2,38*10^4 m3/year. To compare this flux to the amount of precipitation, it can be divided by the total area of the landfill (222.440m2). This gives an upward seepage of 107 mm/year, compared to 844mm precipitation (in reality, the seepage will only take place through the sandy channel fill, or approximately 1/3 of the area).

## 4.2 Water balance with uncertainty range and cost-benefit analysis

For both the current situation and for a variety of scenarios involving different methods of reducing uncertainty, an estimate of error in the outcome of the water balance was calculated. For three fluxes an error reduction did not seem feasible. The flux of irrigation was too small to make a noticeable contribution to error reduction in the outcome of the water balance. In contrast, an error reduction in evapotranspiration would result in a major error reduction in the outcome. However, there is little spatial variation between Schiphol and the Coupépolder. Therefore, error reduction in evapotranspiration was deemed to be unfeasible. The same holds for the deep drainage of the ring drain. This flux is currently measured by doppler-flowmeters. Hence, the most cost-effective method has already been installed.

The methods of the remaining three fluxes were tested using the matlab script (appendix 1a and b), which gave the results that are visually compared in figure 8 and compared to the cost in table 5.

table 5. Mean, standard deviation and 99 percent confidence range of the methods and current situation.

| Test | mean | standard deviation | -99% | +99% | size of range | Initial cost | Yearly recurring cost | Total cost (10 years) |
|---|---|---|---|---|---|---|---|---|
| 1. Current situation. | -2,35E+04 | 1,34E+04 | -5,80E+04 | 1,10E+04 | 6,91E+04 | - | - | - |
| 2. If rain gauge were installed, 15 => 5 % uncertainty. | -2,35E+04 | 8,19E+03 | -4,46E+04 | -2,36E+03 | 4,23E+04 | €1.000 | €650 | €7.500 |
| 3. If shallow drainage were measured with doppler flowmeters. | -2,40E+04 | 1,34E+04 | -5,85E+04 | 1,05E+04 | 6,90E+04 | €10.100 | - | €10.100 |
| 4. If the horizontal permeability were researched, 60 => 20 % uncertainty. | -2,35E+04 | 1,32E+04 | -5,76E+04 | 1,06E+04 | 6,81E+04 | €9.000 | - | €9.000 |
| 5. If method 2 and 4 were implemented. | -2,35E+04 | 7,89E+03 | -4,39E+04 | -3,13E+03 | 4,07E+04 | €10.000 | €650 | €16.500 |

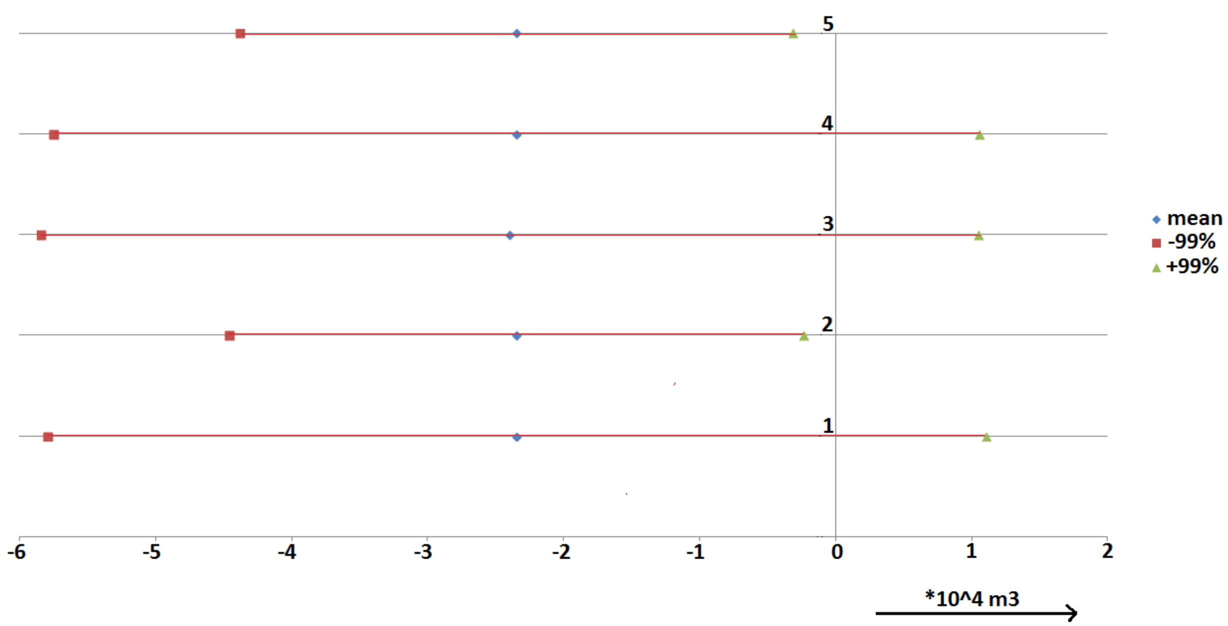


Figure 8. Visual comparison of results shown in table 5.

There are minor deviations from the mean. This is the result of the unilateral error range of shallow drainage (appendix 1b, fluxes out). In tests where the error of this flux is smaller the mean of the flux is higher and therefore the closing term of the water balance is more negative.

For this study especially the upper limit of the 99 % confidence range is used. Currently, the upward seepage has a confidence lower than 95 percent. A study into the horizontal permeability of the Holocene sediments around the landfill only has a minor influence on the upper limit of the 99 percent confidence range: from $1{,}10 * 10^4$ infiltration per year to $1{,}06 * 10^4$ infiltration per year. In combination with the high initial cost of €9.000, this method has a low cost-effectiveness. Measuring shallow drainage has approximately the same influence as studying the horizontal permeability. As with studying horizontal permeability, it is the high initial cost (€10.000) that makes this method undesirable. In contrast, if an in situ automatic rain gauge were installed, the upper limit of the 99% confidence range would shift from $1{,}10 * 10^4$ infiltration to $2{,}36 * 10^3$ m3/year *upward seepage*. The benefit in certainty of the data was only 7,5 percent. It is the size of this flux that provides the large benefit in the outcome of the result. To illustrate this effect, reducing the error in shallow drainage from 100 to 5 percent is far less beneficial than lowering the error in precipitation by 7,5 percent, because its flux is only 1,5 percent of the flux of precipitation. Comparing test 2 and 5 shows the small relative contribution of measuring horizontal permeability.

To gather precipitation data for a meaningful comparison with the amount of rainfall at weather station Schiphol, at least a decade of measuring would be required. This would cost €1.000+10*€650=€7.500. Therefore, this method costs less than researching horizontal permeability or measuring the flow of shallow drainage. It is also significantly more beneficial.

# 5. Discussion

In this chapter, the methods and results will be critically examined and compared to other studies. Firstly, improvements over earlier water balances will be discussed. Secondly, possible improvements in the method will be discussed. Thirdly, the result of the water balance will be compared to other water balances and to data of hydraulic heads in the landfill and in the first aquifer. Finally, a possibility of solving the question of infiltration versus upward seepage is highlighted.

**Improvements over earlier water balances**

This study is an improvement over the earliest water balances of TNO (1980) and Iwaco (1985) because they did not yet reckon with later artificial fluxes and a change in vegetation. A younger study of Royal Haskoning in 2006 did take into account the new fluxes, but did not mention irrigation. Secondly, a 100 percent grass surface was used in their evapotranspiration calculation instead of 80 percent grass and 20 percent trees. Thirdly, Royal Haskoning miscalculated the surface underlain by the sand-bentonite layer (municipality Alphen aan den Rijn, 2007). In their water balance a value of 27500 m2 instead of 29500 m2 was used. This resulted in approximately 1700 m3 overestimation.

Fourthly, Δh was calculated as the difference in height between the source of the flux and the depth of the ring drain. However, it is the difference between the source and the hydraulic head next to the drain which dictates the amount of suction towards the drain. The hydraulic head is not dictated by the depth of the drain but rather by:

1. The water levels at which the pumping stations are programmed to start and stop pumping.
2. The amount of entrance and pipe resistance of the drainage pipe.

Using the approach of Royal Haskoning increases the flux by 6.260 m3.

Finally, the study lacks an error estimate, which makes the outcome less valuable.

**Possible improvements in the method**

The aims of this study were to minimize error in the current calculation and to propose methods to further minimize error in future water balances. In both, minimizing error in the largest fluxes is most important because these errors influence the outcome most. The evapotranspiration term was calculated using Makkink evaporation data from KNMI. Makkink evapotranspiration is only dependent on temperature and radiation data, which makes it simpler but possibly more prone to error. The equation was specifically developed for well-watered grass surfaces in a temperate climate. Since the area under study consists for 80 percent of well-watered grassland the outcome of the Makkink equation will be relatively accurate. A possible improvement would be to use the Penman-Monteith equation. In comparison to the Makkink equation, this method is far more elaborate. It needs data of minimum, maximum and mean temperature, radiation, wind speed and humidity (Allen et al., 1998). Compared to this method, the Makkink method lacks an energy input (wind) and a term for the resistance against evapotranspiration (using relative humidity). The Penman-Monteith equation simulates the natural process of evapotranspiration more realistically and could therefore have a lower amount of uncertainty. All data require to calculate Penmann-Monteith evapotranspiration are available at KNMI weather station Schiphol. This study did not use Penmann-Monteith evapotranspiration because of difficulties with the computation.

Another possible point of improvement lies with the computation of the error in shallow drainage. Because this error is unilateral, all values higher than the mean were converted to the mean value in matlab. An effect of this computation was a lowering of the mean shallow drainage. As a result, the mean of the outcome of the water balance shifted by -500 m3/year. Furthermore, converting the positive halve of the normal distribution to the mean value led to peaks around the mean of the normal distribution of the result (fig. 9). Alternatively, shallow drainage could have been computed with a lower mean and a bilateral error to avoid these complications.

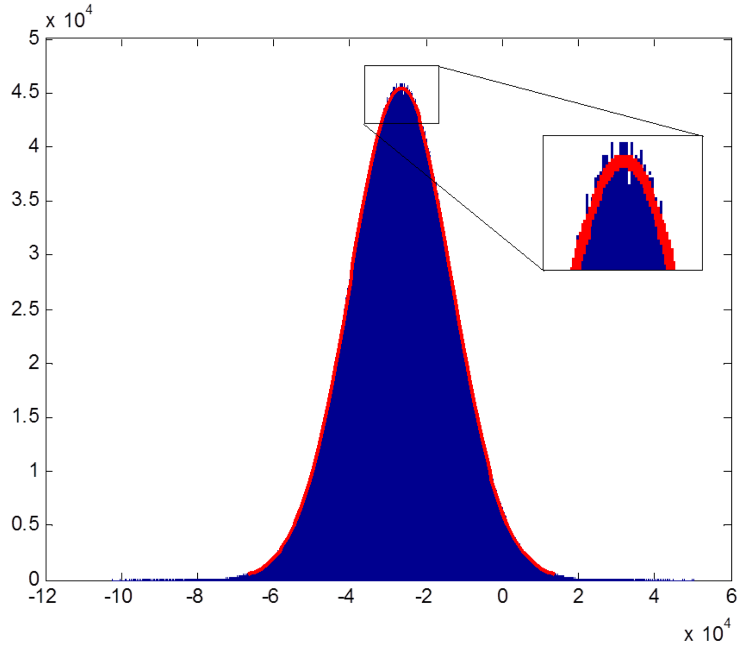


Figure 9. Normal distribution of the result of the water balance.

A possible error in the water balance is the calculation of the flux from side to ringdrain. The horizontal permeability is not well known. Another approach would be to estimate that 50 percent of the ringdrain flux originates from the area around the landfill and 50 percent comes from within the landfill. In summer, when the groundwater level in the landfill lies around -1,5 m, the situation on both sides is similar: both flows pass through Holocene clays. During this season this would be a reasonable assumption. However, in winter, when the groundwater level varies around -0,8 m, the flow from the landfill can use an overflow route depicted in figure 12. As long as the groundwater level is higher than -1,0 m NAP, water from the landfill will flow through highly permeable sands. Thus, during this season the flux from the landfill will be significantly higher than the flux from outside.

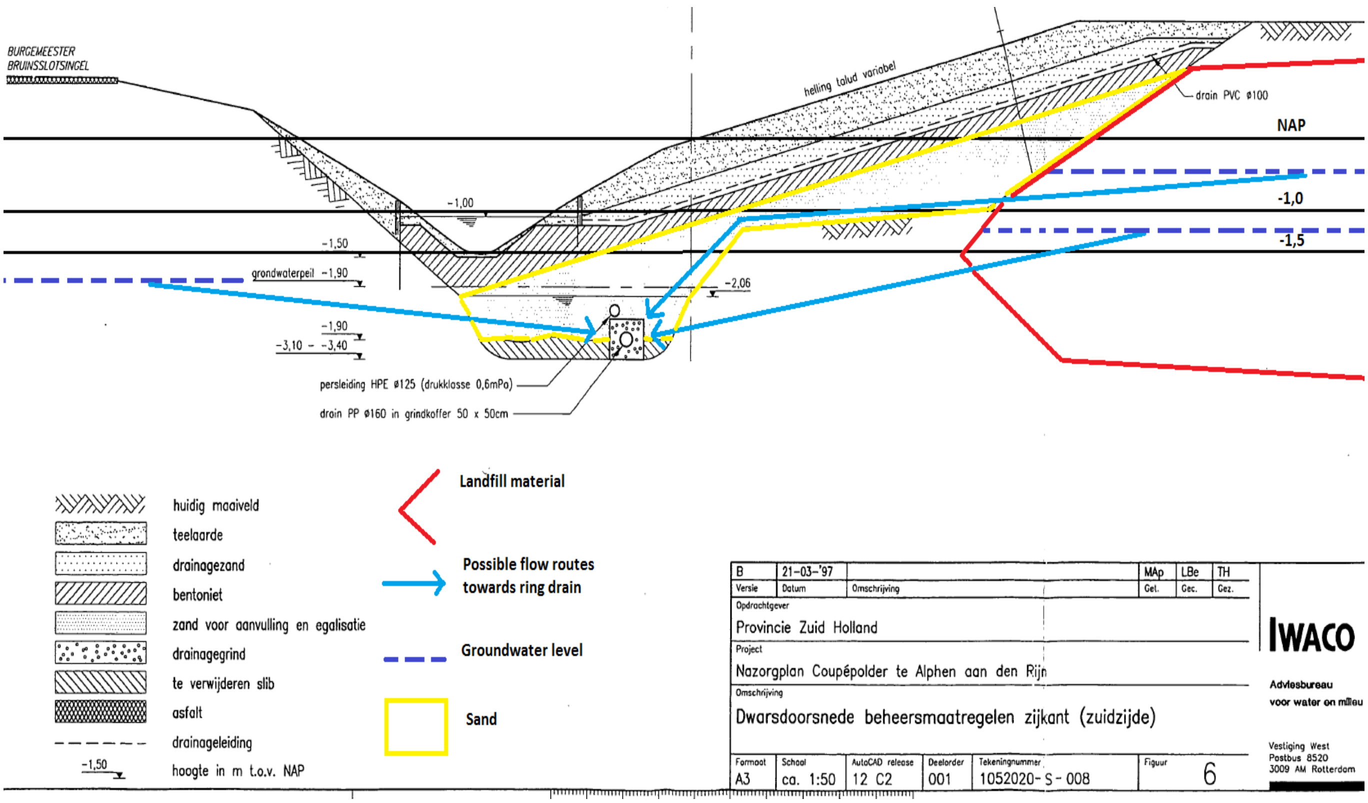

Figure 12. Possible routes for groundwater flow towards the ring drain

For the sake of discussion the effect of assuming a 50 percent share of groundwater from outside the landfill will be discussed.

In the current calculation, the flux leaving the landfill is:

$$ringdrainage - flux\ from\ side\ to\ ringdrain = 7{,}48 * 10^4 - 7{,}58 * 10^3 = 6{,}72 * 10^4$$

If 50 percent of the water came from outside the area, the effective flux leaving the landfill would be:

$$\frac{7{,}48 * 10^4}{2} = 3{,}74 * 10^4$$

The new waterbalance would then be:

Table 7, new water balance of the Coupépolder.

| Flux | amount (*$10^4$ m3) |
|---|---|
| Precipitation | 16,28 |
| Flux from side to ringdrain | 3,74 |
| Irrigation | 0,00 |
| Evapotranspiration | -11,71 |
| Ringdrainage | -7,48 |
| Shallow drainage | -0,23 |
| Interaction with aquifer | 0,60 |

Thus, the mean of the new outcome would be an infiltration. Using the same confidence range as in the original outcome of the water balance, the outcome would lie between $-2{,}86 * 10^4$ and $+4{,}06 * 10^4$.

**Comparison of the outcome with earlier water balances and with measured hydraulic heads**

Table 6. Calculated infiltration values by different studies. Negative values are upward seepage from the first aquifer to the landfill.

| | Infiltration (m3/year) | % error | Source |
|---|---|---|---|
| TNO, 1980 | 30.000 | 59 | TNO, 1990, municipality Alphen aan den Rijn, 2007 |
| Iwaco, 1985 | 26.693 | n.a. | Iwaco, 1985 |
| Royal Haskoning, 2006 | -36.260 | n.a. | Royal Haskoning, 2006 |
| This study | -23.770 | 49 | n.a. |

There is a marked difference between the results of the different water balances (table 6). As argued in the introduction, the two youngest water balances are most analogous to the current situation. It is therefore curious that the upward seepage calculated in both Royal Haskoning 2006 and this study seems contradictory to the hydraulic heads measured in the first aquifer and the landfill. The pumping stations of the ring drain maintain a hydraulic head in the landfill near the drain between -2,20 m to -1,50 m NAP (Promeco, 1998), which may even be higher in winter. As an example, the hydraulic heads in the winter of 2007 ranged between -0,9 and -1,35 m NAP (Bodemzorg, 2008). Hydraulic heads measured in the first aquifer ranged between -3,3 NAP south of the landfill and -3,9 m NAP north of the landfill (fig. 10). Thus, data of hydraulic heads point towards infiltration.

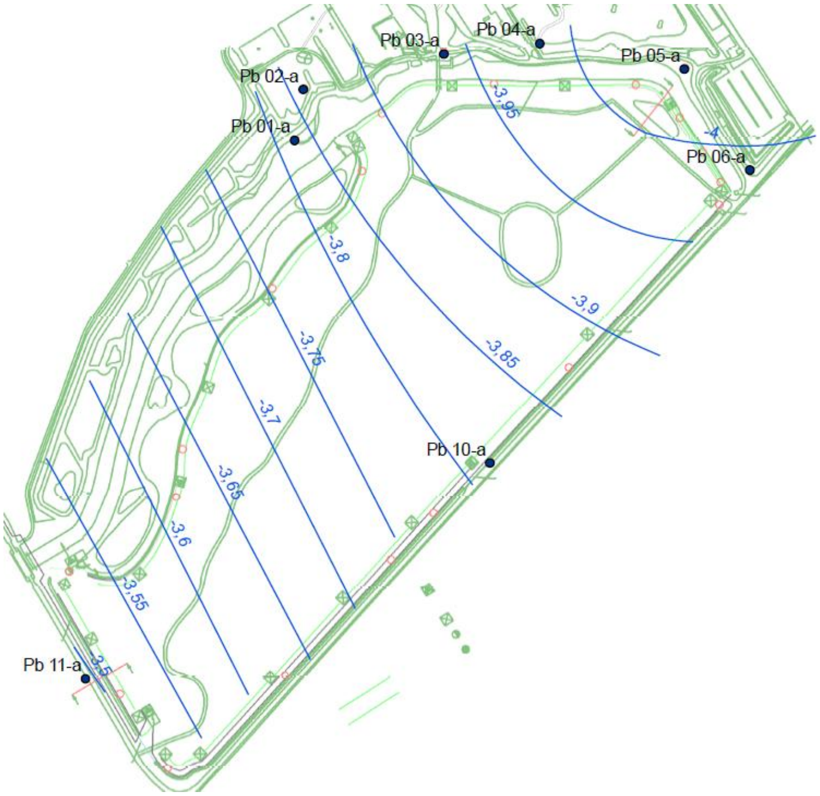


Fig. 10. Isohyetal lines of hydraulic heads of the first aquifer. Source: Iwaco, 1997.

Hence, either the hydraulic heads in the landfill, the hydraulic heads of the first aquifer or the two youngest water balances are incorrect. The hydraulic heads of the landfill are measured along the edge of the landfill. They correspond with the water levels maintained in the pumping stations. One type of error in these heads could come from the fact that they are measured along the edge of the landfill: hydraulic heads in the middle might be lower. However, because the landfill is elevated, a bulge in the water table is far more likely. Another possibility of error was given by Iwaco, 1997. In this study it was noted that there are perched water tables in the landfill, mainly under the higher parts of the landfill. Therefore, a perched water table could have been measured instead of the actual water table (fig. 11).

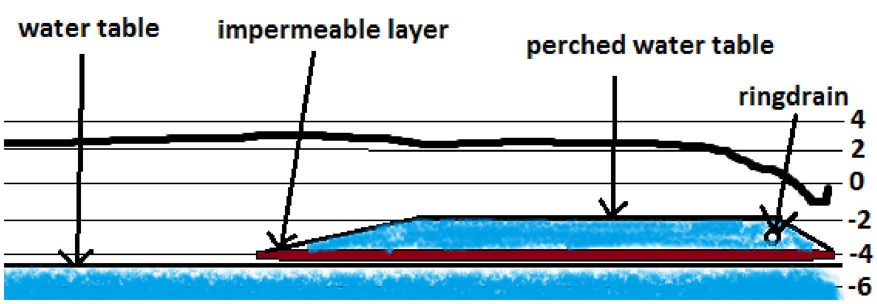


figure 11. Perched water table in the landfill.

For multiple reasons this perched water table scenario seems far-fetched: what does the impermeable layer consist of?  In drillings described by Iwaco, 1988, there is no discrimination between different types of material in the landfill. However, it seems unlikely that the landfill material has horizontal

impermeable layers due to its inhomogeneity. Moreover, it is questionable whether there would be enough water in the perched aquifer to feed the ring drain the amounts of water measured by the pumping stations. To accomplish this amount of water the impermeable layer would have to be widespread which seems unlikely due to the inhomogeneity in the landfill.
There is also the possibility that the water table of the first aquifer is higher under the landfill then the -3.3 and -3.9 m NAP measured respectively south and north of the landfill. However, these values correspond with the regional direction of flow to the north/northeast. It is therefore very unlikely that the water table in the first aquifer under the landfill is higher than -3.3 m NAP (appendix 12).

**Future research**

The most important goal of future research should be to irrefutably solve the question of infiltration versus upward seepage. This question could possibly be solved by tritium dating of the groundwater in the landfill (G.M. Ganssen, 2014). The tritium dating method uses tritium concentrations in groundwater. In the 1950s many governments started nuclear bomb testing (W.E. Motzer, date unknown). Tritium from these tests dissolved into groundwater, which led to concentrations of around 20 to 30 times the natural background concentration in the 1960s and 1970s. Hence, the water can be divided in five age classes (W. E. Motzer, date unknown):

- <0.8 TU indicates submodern water (prior to 1950s)
- 0.8 to 4 TU indicates a mix of submodern and modern water
- 5 to 15 TU indicates modern water (<5 to 10 years)
- 15 to 30 TU indicates some bomb tritium
- >30 TU: recharge occurred in the 1960s to 1970s

(1 TU is one tritium atom in $10^{18}$ hydrogen atoms)

Large scale dumping in the Coupépolder began in 1972 (coupepolder.nl, 2014). Thus, percolation fluids of the landfill cannot be older than from 1972. Tritium concentrations of this water will be between 30 and 5 TU. In contrast, water from the first aquifer will be from before the 1950s and will therefore have a concentration below 0,8 TU. If a sample of water were taken in the sandy channel fill, at a depth around -5 m NAP, a concentration below 0,8 TU would indicate water from the aquifer below and thus an upward seepage. A concentration above 5 TU would indicate percolation fluids and thus an infiltration. A concentration between 0,8 and 5 TU would indicate a mixture of the two types of water and would therefore be an ambiguous result. If this were the case, a further test could be to lower the pumping levels of the pumping stations of the ring drain. This would lower the hydraulic head in the landfill, consequently increasing the possibility of upward seepage (J. Groen, 2014). Then, a new tritium dating would possibly find a concentration below 0,8 TU.

# 6. Conclusion

This study aimed to provide an improved water balance by reconsidering and recalculating all fluxes and by including an error estimate. In addition, this study set out to propose the most cost-effective method for reducing error in future water balances. The outcome of the current water balance is an upward seepage of $2{,}38 * 10^4$ m3/year. For a 99 percent confidence range the result is ambiguous and ranges between $5{,}38 * 10^4$ m3/year upward seepage and $1{,}075 * 10^4$ m3/year infiltration. However, if the assumption were made that the ring drain is fed for 50 percent by water from outside the landfill, the result would be a minor infiltration of $0{,}60 * 10^4$ m3/year. This assumption cannot be true because in winter the water from the landfill follows a route with significantly higher permeability than the route of the water from outside the area. However, this example shows the large effect of making different assumptions about the hydrological system of the landfill. The most cost effective method to reduce uncertainty in the data and consequently improve the outcome of future water balances, is installing an automatic rain gauge at landfill 'the Coupépolder'. This would lower uncertainty of the result enough to obtain 99 percent confidence in the current outcome. However, as shown by the example of assuming that 50 percent of the water from the ring drain originated from outside the landfill, most uncertainty actually lies with assumptions and interpretations of our current data. Therefore, further research is needed into the complex hydrological system of the landfill. This research should focus on whether there are fluxes missing in the most up-to-date water balances and whether we fully comprehend what happens in, under and besides the landfill.

# 7. References


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# 8. Appendix

## 1. Matlab scripts used for the water balance

### 1.1. Matlabscript which calculates input for the main script

```
datawaterbalance.m

surfacesandbento=29500; %area overlain by sand-bentonite layer (substractable
from top of hydrological system (m2)
surfacerunoff=3600; %area which undergoes runoff. The runoff from this area
does not infiltrate within the
%boundaries of the hydrological system (m2)
surfacelandfill=222440; %total surface landfill (m2)
surfaceevaporation=surfacelandfill-surfacesandbento;%192940 m2
surfaceinfiltration=surfacelandfill-surfacesandbento-surfacerunoff;%189340 m2

%fluxes in
meanprecipitation=(843.8466667*10^-3)*surfaceinfiltration;
%stdev precipitation: 15 percent now, 7.5 percent with in situ rain gauge
%this uncertainty is taken to be 1.96 sigma (95% confidence interval).
%Thus, 1 standard deviation (1 sigma) is:
stdevprecipitation=meanprecipitation*0.15/1.96;


%irrigation zero (no net throughflow)
%meanirrigation=
%stdevirrigation=

%flux from area around landfill towards ringdrain (meansidetoringdrain)
%calculation:
%Q=k*D*(dh/dx)*L*365.25
%Q in m3/year
k=0.03; %(mean horizontal permeability)
d=10;%d: thickness holocene=10m
d2=5;%(5m for heemgebied (RH'06)
year=365.25;%days in year
%L=length of part of surficial water around landfill
%QHeemgebied1 (heemgebied part 1,peil Kromme Aar), flow through lower 5 m of
holocene>d=5
%L=600,dh=2.37,dx=50
%QHeemgebied2=(part 2,peil Heemgebied), flow through upper 5m=>d=5
%L=600, dh=1.27, dx=15
%QAarkanaal,
%L=800, dh=2.60, dx=25
%QKrommeaar+damwand=0 because of dam
%Qzegerplas (side Burgemeester Bruin Slotsingel,peil Zegerplas)
%L=250, dh=1.4, dx=100
Qheemgebied1=k*d2*(2.37/50)*600*year;
Qheemgebied2=k*d2*(1.27/15)*600*year;
Qaarkanaal=k*d*(2.60/25)*800*year;
Qkrommeaar=0;
Qzegerplas=k*d*(1.4/100)*250*year;
```

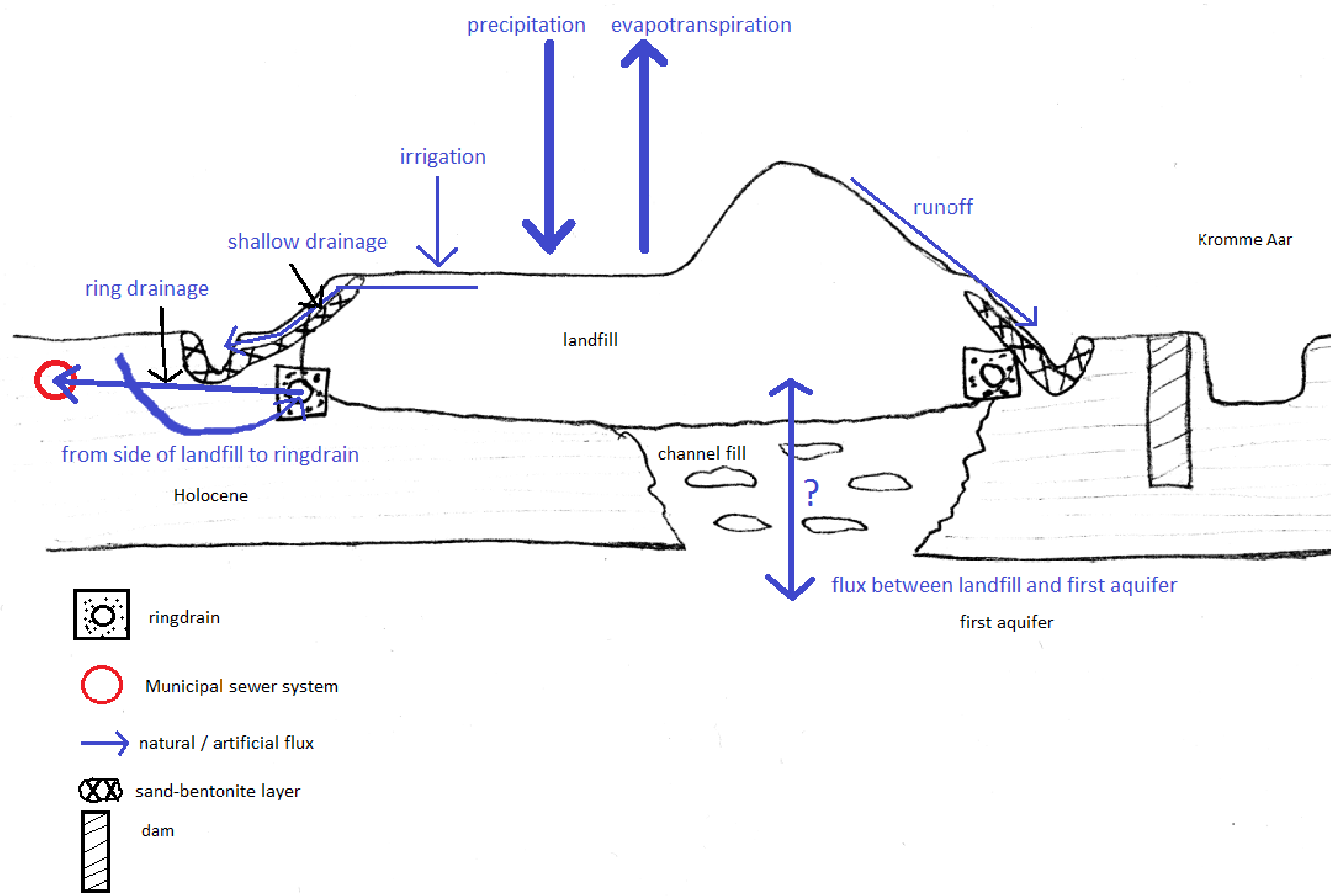
```
meansidetoringdrain=Qheemgebied1+Qheemgebied2+Qaarkanaal+Qkrommeaar+Qzegerplas
;
%stdevsidetoringdrain: source: Royal Has '06, own calculations (see
%meth.onz.reductie)
%approximately 50 percent =1.96 stdev
stdevsidetoringdrain=meansidetoringdrain*0.60/1.96;


%fluxes out


%evapotranspiration using 17 percent extra evaporation (due to
%interception) (M. Waterloo, 26-05-2014) of poplars and maple during fully
leafed season (approx 20th
%april-10th october (Guidi et al, 2007)(day of year: schrikkel: 111-284,
normal: 110-283) . Percentage of surface poplar/maple: 22. cropfactorPoplar:
vector with 1,17 for leafed season, 1,00 for winter. cropfactorgrass: 1,00
year-round.
%percent (Google earth surface calculator, calculations Hans van Hateren)
evatrans=makkink.*((cropfactorPoplar*0.22)+(cropfactorgrass.*0.78));
meanevatrans=mean(evatrans)*1*10^-3*365.25*surfaceevaporation;
stdevevatrans=meanevatrans*0.075/1.96;


%ringdrain from reports '96 - '11
meanringdrain=74792.4375; %m3
% +-5 percent error if measured with dopplermeter (check with
%promeco)=1.96*stdev
stdevringdrain=meanringdrain*0.05/1.96;


%shallowdrain
%10133m2 drainage area (see datafile, appendix map of shallow drainage)
%=>maximum drainage (*precipitation surplus)=
meanshallowdrain=(0.844-0.588)*10133; %2.594*10^3 m3
stdevshallowdrain=meanshallowdrain*1.00/1.96;
```

## 1.2. Matlab script for water balance with random number generator

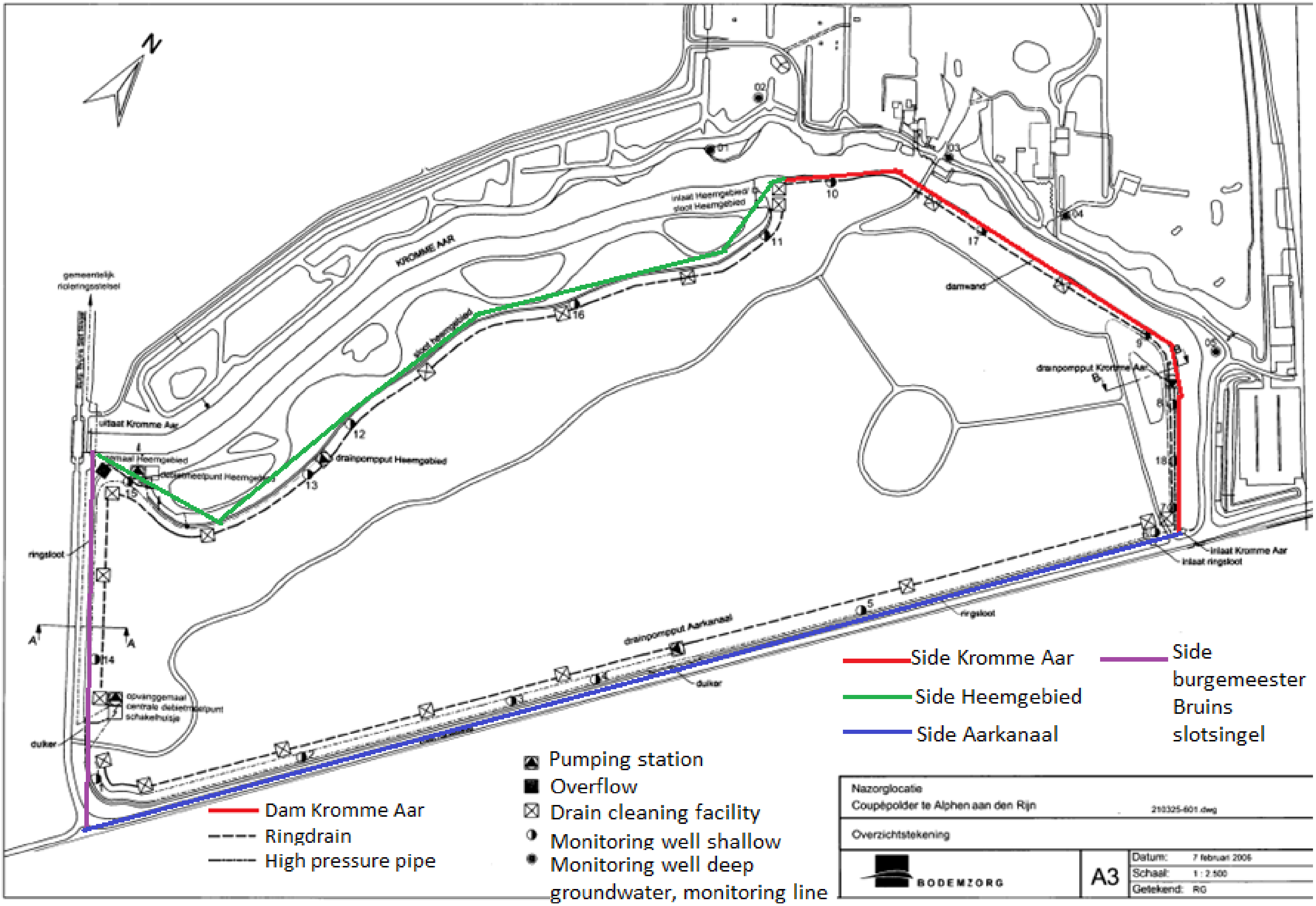
```
waterbalance.m

%randn(n,b) returns matrix of normally distributed pseudorandom numbers
%with size n*b. n= the larger the more outcomes, b=1 (thus, vector).

clear;
load('cropfactorsandmakkink');
run('datawaterbalans');
n=1*10^8;
%Fluxes into landfill (fluxin)

precipitation= meanprecipitation + stdevprecipitation*randn(n,1);
%irrigation = meanirrigation + (stdevirrigation/1.96)*randn(100000,1)
%set to zero
sidetoringdrain=meansidetoringdrain+stdevsidetoringdrain*randn(n,1);

fluxin=precipitation+sidetoringdrain;

%Fluxes out of landfill(fluxout)
evatrans= meanevatrans+stdevevatrans*randn(n,1);
ringdrain= meanringdrain+stdevringdrain*randn(n,1);
shallowdrain=meanshallowdrain+stdevshallowdrain*randn(n,1);
%meanshallowdrain was max value, so only on one side deviation, convert
%values bigger than mean to mean
shallowdrain(shallowdrain>meanshallowdrain)=meanshallowdrain; %this does have
an influence on the mean,
%mean now not centered on the aforementioned mean. The new mean is smaller
than the old mean because values
%above the old mean are revalued to beiing equal to the old mean.

fluxout=evatrans+ringdrain+shallowdrain;


%flux between landfill and aquifer, result water balance, called
%fluxIA(interaction aquifer)
fluxIA = fluxin-fluxout;
%fluxIA is vector with results from water balance. Its vector has the same
size
%as the vectors of the data.
%The results are plotted using histfit=> normaal distribution is plotted.
%If fluxIA is positive there is a netto surplus of water in the landfill
%this water will be given to the wvp
%fluxIA negative means flux from wvp to landfill.

histfit(fluxIA);

%std(x,1) returns standard deviation of x, normalized by n (number of
%datapoints)
stdevfluxIA=std(fluxIA,1);

%m = mean(pd), returns mean of probability distribution (pd)
meanfluxIA=mean(fluxIA)
%95%confidence interval: (1.96stdev to each side)
```

```
min95fluxIA=meanfluxIA-1.96*stdevfluxIA
plus95fluxIA=meanfluxIA+1.96*stdevfluxIA
%99 percent confidence interval (2.58 stdev to each side):
min99fluxIA=meanfluxIA-2.58*stdevfluxIA
plus99fluxIA=meanfluxIA+2.58*stdevfluxIA
```

## 2. Sketch of the hydrological system of landfill the Coupépolder



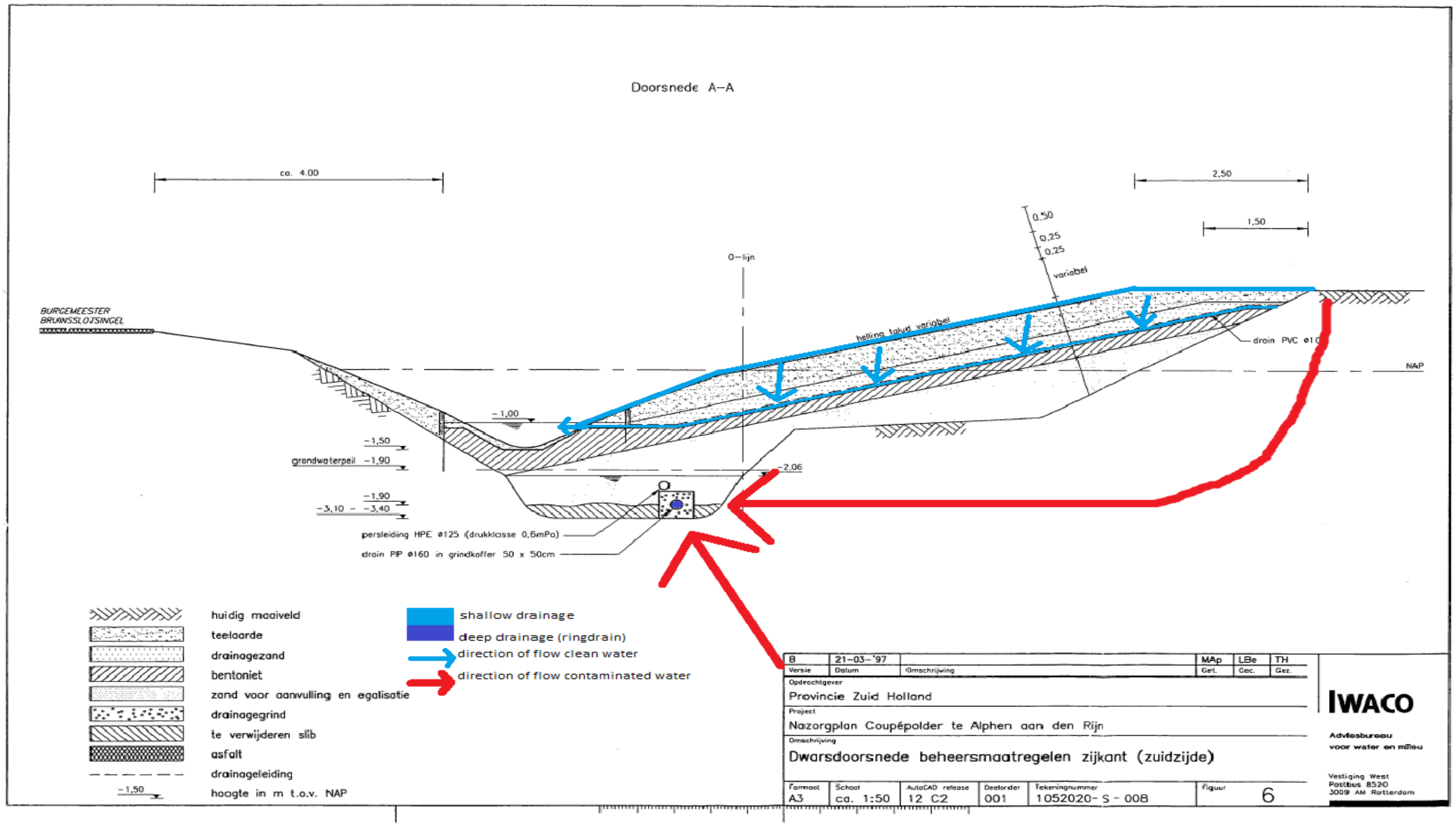
## 3. Overview of the Coupépolder with implemented measures



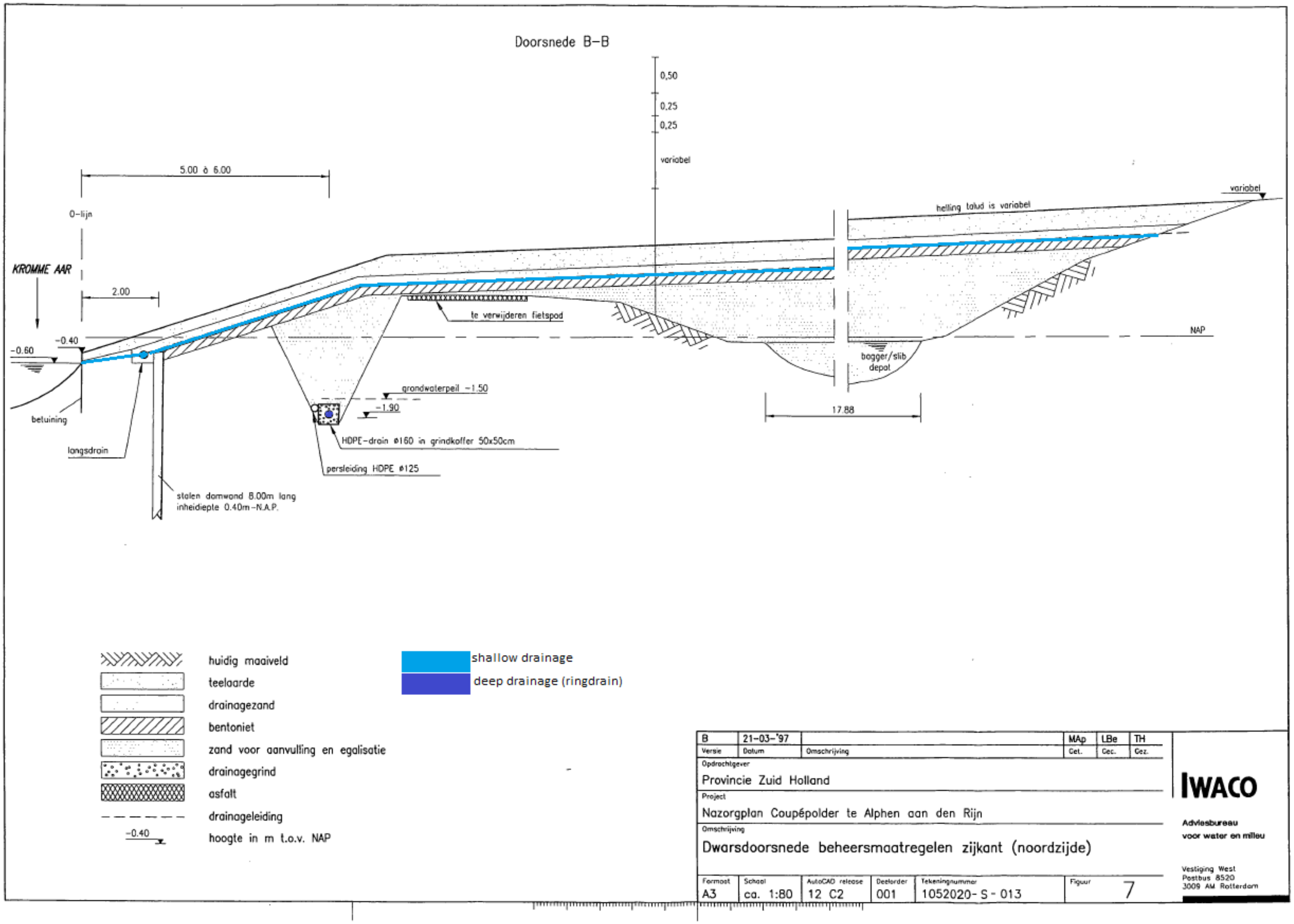
# 4. Profiles of measures to prevent the sides of the landfill from leaking

In this appendix two profiles of the measures taken on the sides of the landfill are shown (Iwaco, 1997). 4.1 shows a profile of the side of the landfill along the Aarkanaal, representative for all sides except the north side. It depicts the sand-bentonite layer and the deep- and shallow drainage, as well as the flow directions of clean and contaminated water. 4.2 depicts the situation at the north side, along the Kromme Aar. The dam depicted here prevents water from the Kromme Aar from flowing towards the ringdrain.

## 4.1. Profile of measures along the Aarkanaal

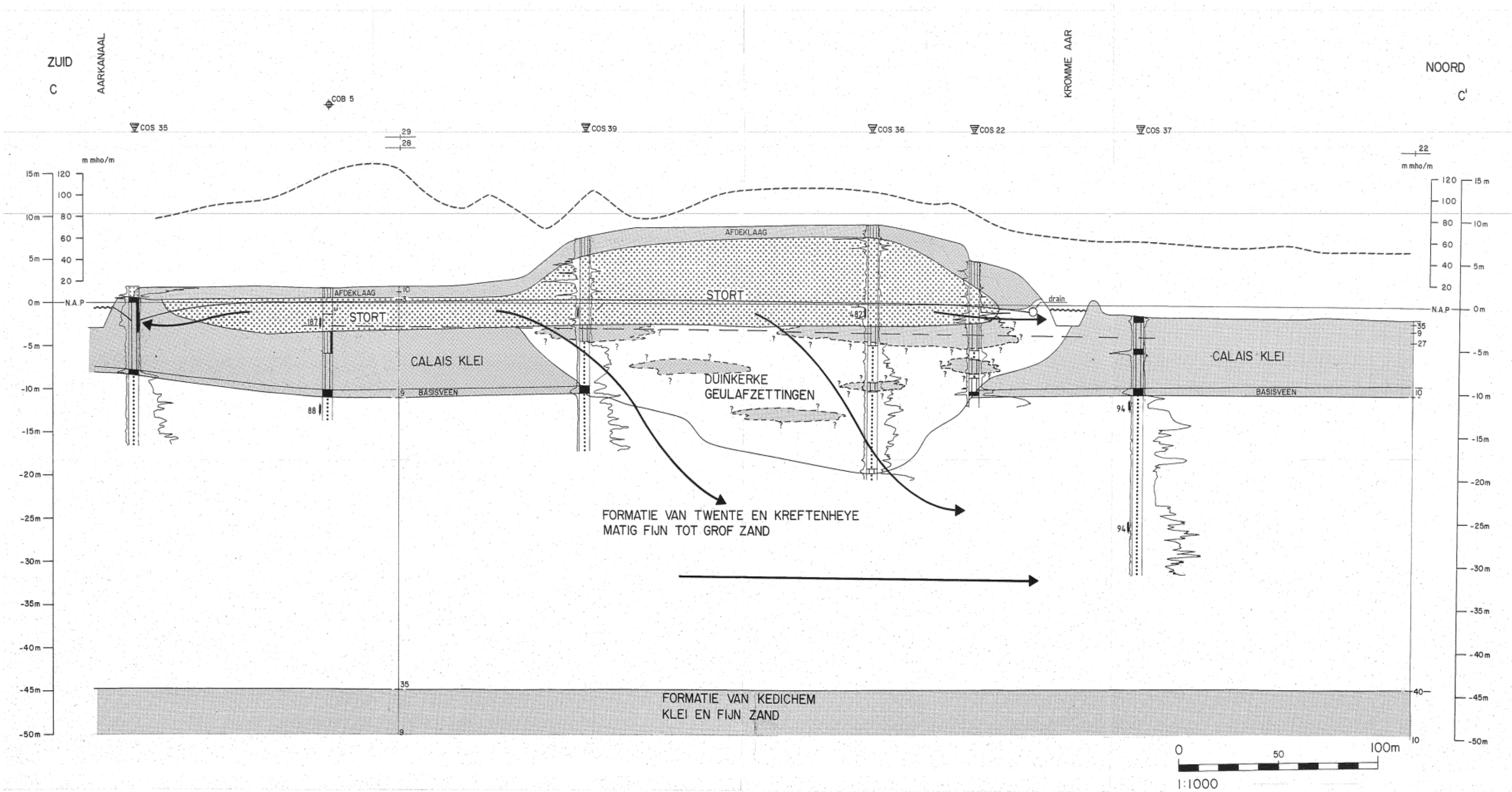


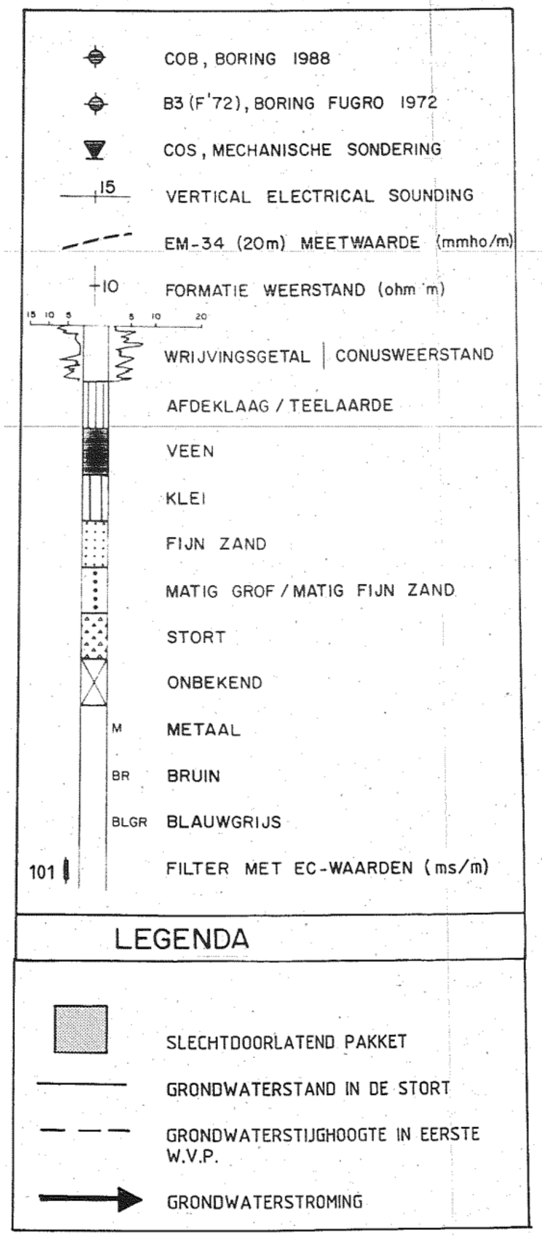
## 4.2. Profile of measures along the Kromme Aar

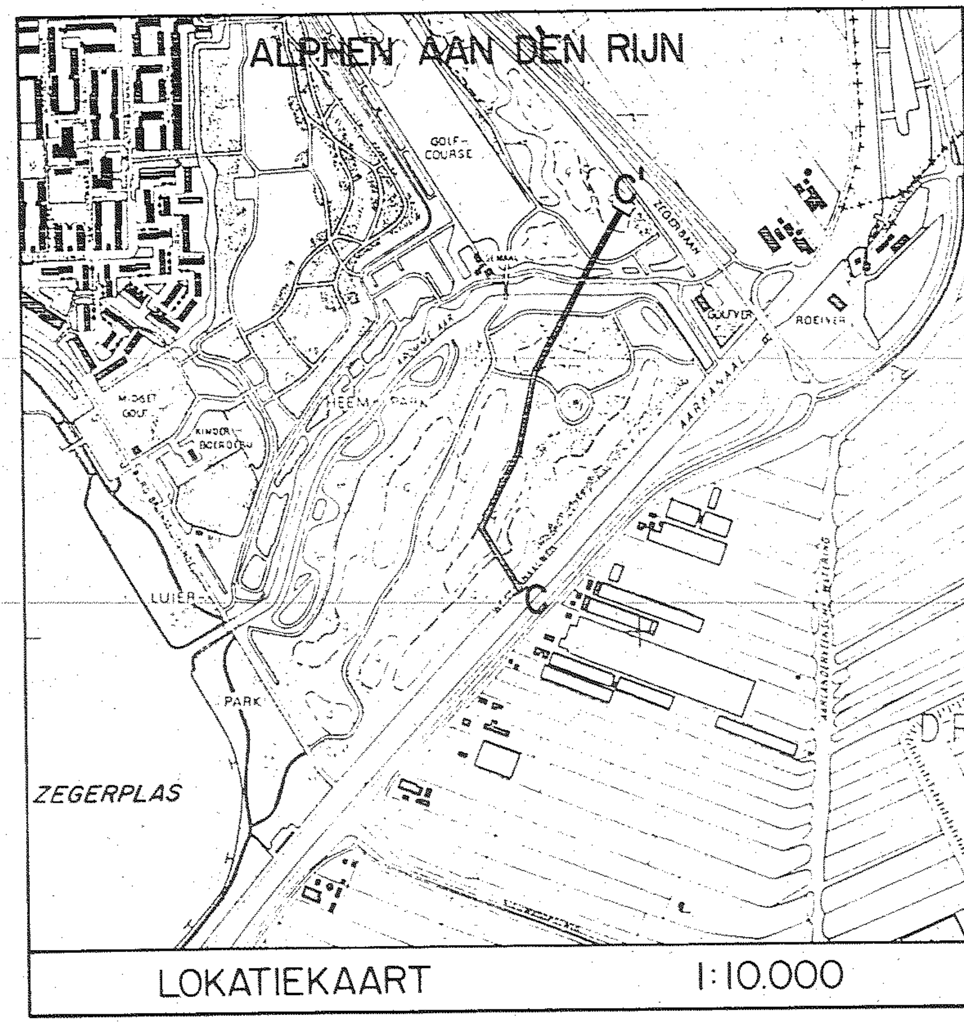


## 5. Geological profile along C-C'

(IWACO, 1988, Vervolgonderzoek, interimrapport fase 1a). For legend and location, see next page.

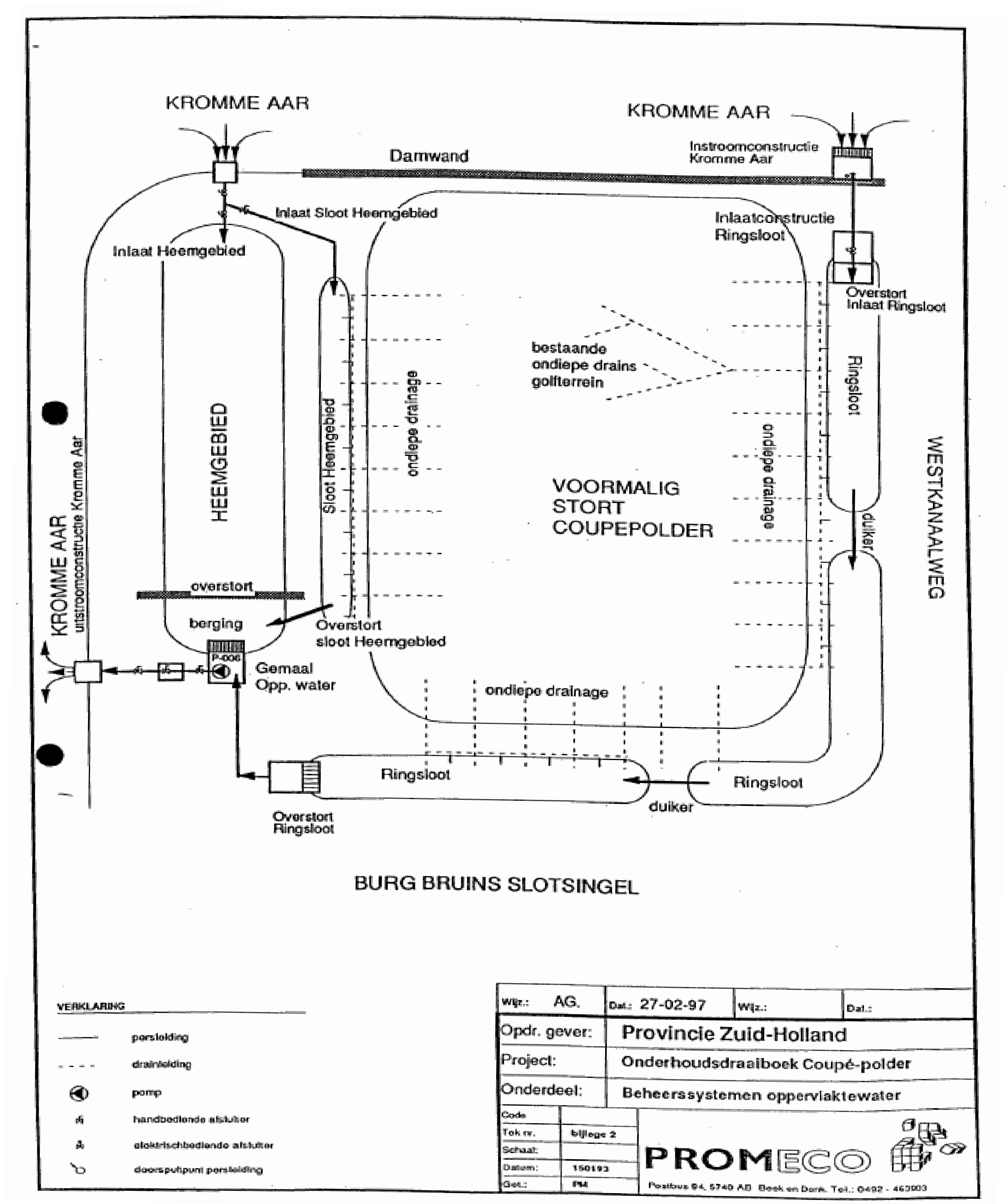



COB, BORING 1988
B3 (F'72), BORING FUGRO 1972
COS, MECHANISCHE SONDERING
15
VERTICAL ELECTRICAL SOUNDING
EM-34 (20m) MEETWAARDE (mmho/m)
10
FORMATIE WEERSTAND (ohm m)
WRIJVINGSGETAL | CONUSWEERSTAND
AFDEKLAAG / TEELAARDE
VEEN
KLEI
FIJN ZAND
MATIG GROF / MATIG FIJN ZAND
STORT
ONBEKEND
M METAAL
BR BRUIN
BLGR BLAUWGRIJS
101 FILTER MET EC-WAARDEN (ms/m)
LEGENDA
SLECHTDOORLATEND PAKKET
GRONDWATERSTAND IN DE STORT
GRONDWATERSTIJGHOOGTE IN EERSTE W.V.P.
GRONDWATERSTROMING


ALPHEN AAN DEN RIJN
GOLF-COURSE
C'
C
ROEIVER.
LUIER-
PARK
ZEGERPLAS
LOKATIEKAART
1:10.000

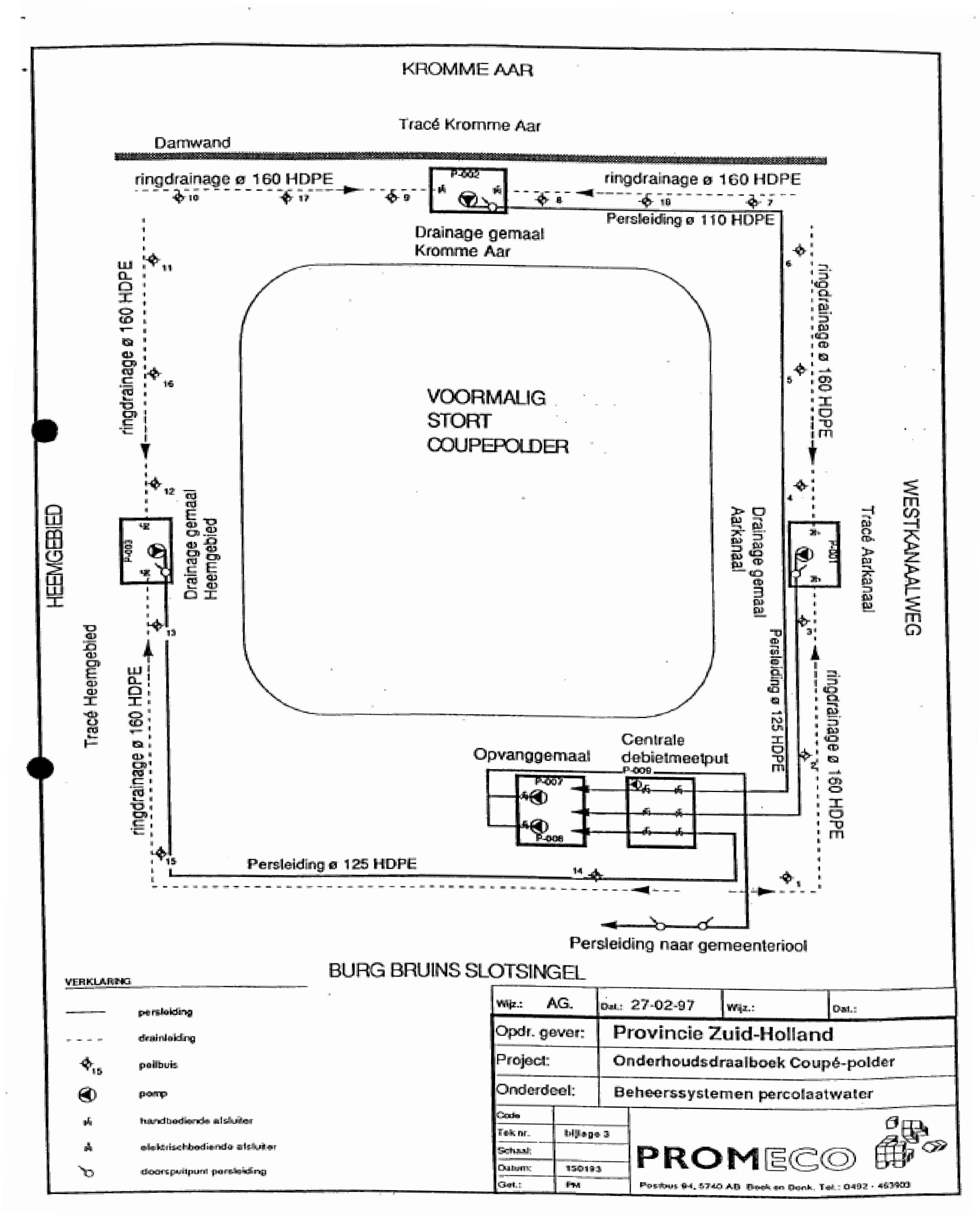
## 6. Sketch of artificial surface water system

(Promeco, 2002, Jaarverslag beheer 2001)



## 7. Sketch of contaminated deep water system

(Promeco, 2002, Jaarverslag beheer 2001)



## 8. Calculation of surface drained by shallow drains

Scale map: 863.08/0.227=3802

Scale: 1:3802

Distance between drains: 2 mm=> fits more or less with Wikipedia (10 m between drains)=> draw 2 mm around drains in map to get drained surface.

Drained area (sand-bentonite layer part of the landfill is not added to the area):

96+186+144+292+100+298=1116mm2=0.001116m2 on map. Scale: 1:3802=> 3802^2*0.00116=16768 m2 (11.3 percent of infiltration area).

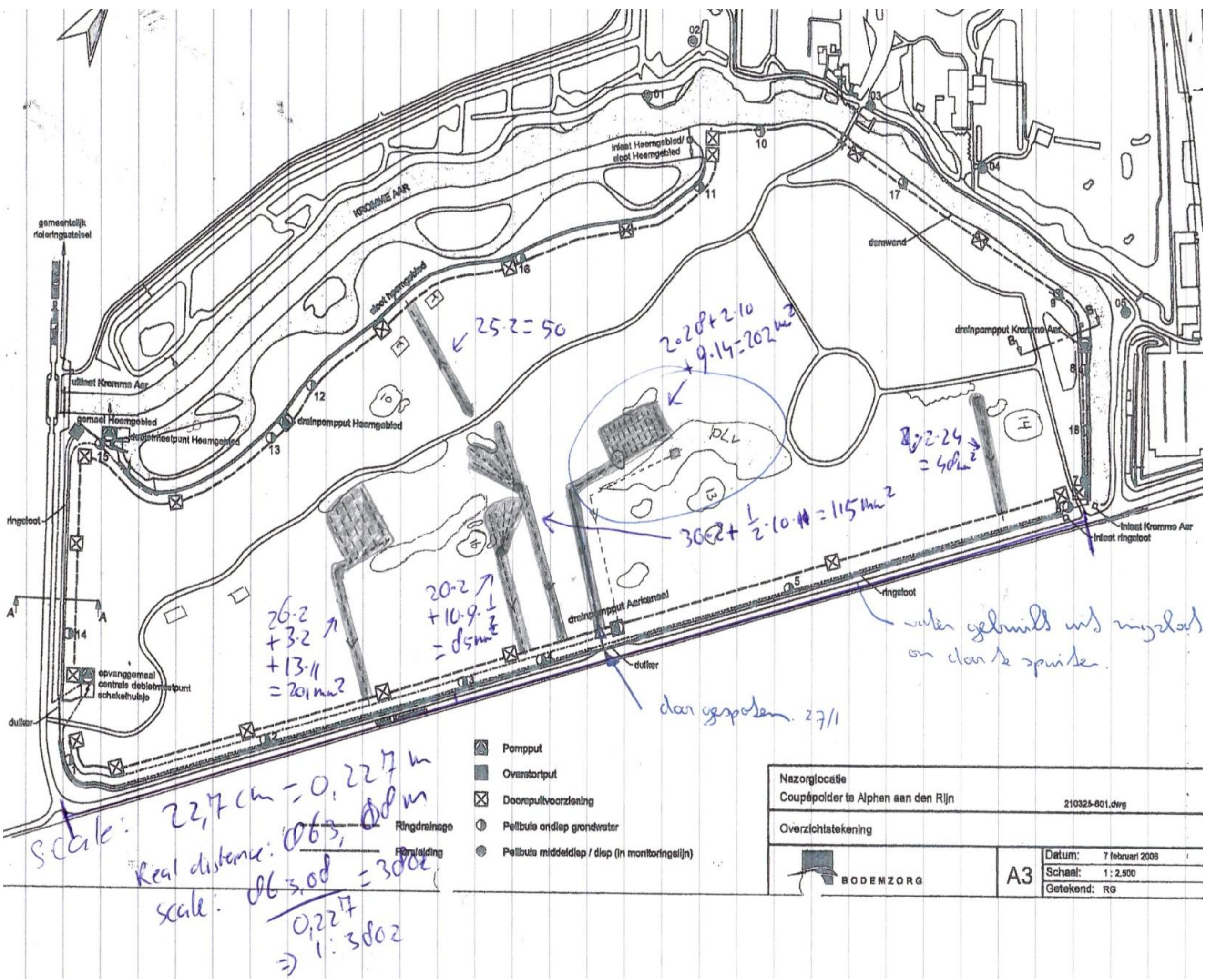
Neerslagoverschot (nog nieuwe verdamping nodig):(.844-.416)*16768=7176.7 m3

Distance between drains: 2mm=> drain can drain on each side: (2/2)*10^-3*3802=3.8 m

Draw on map: 1 mm around drains=> calculate surface: 50+202+48+115+85+201=701mm2

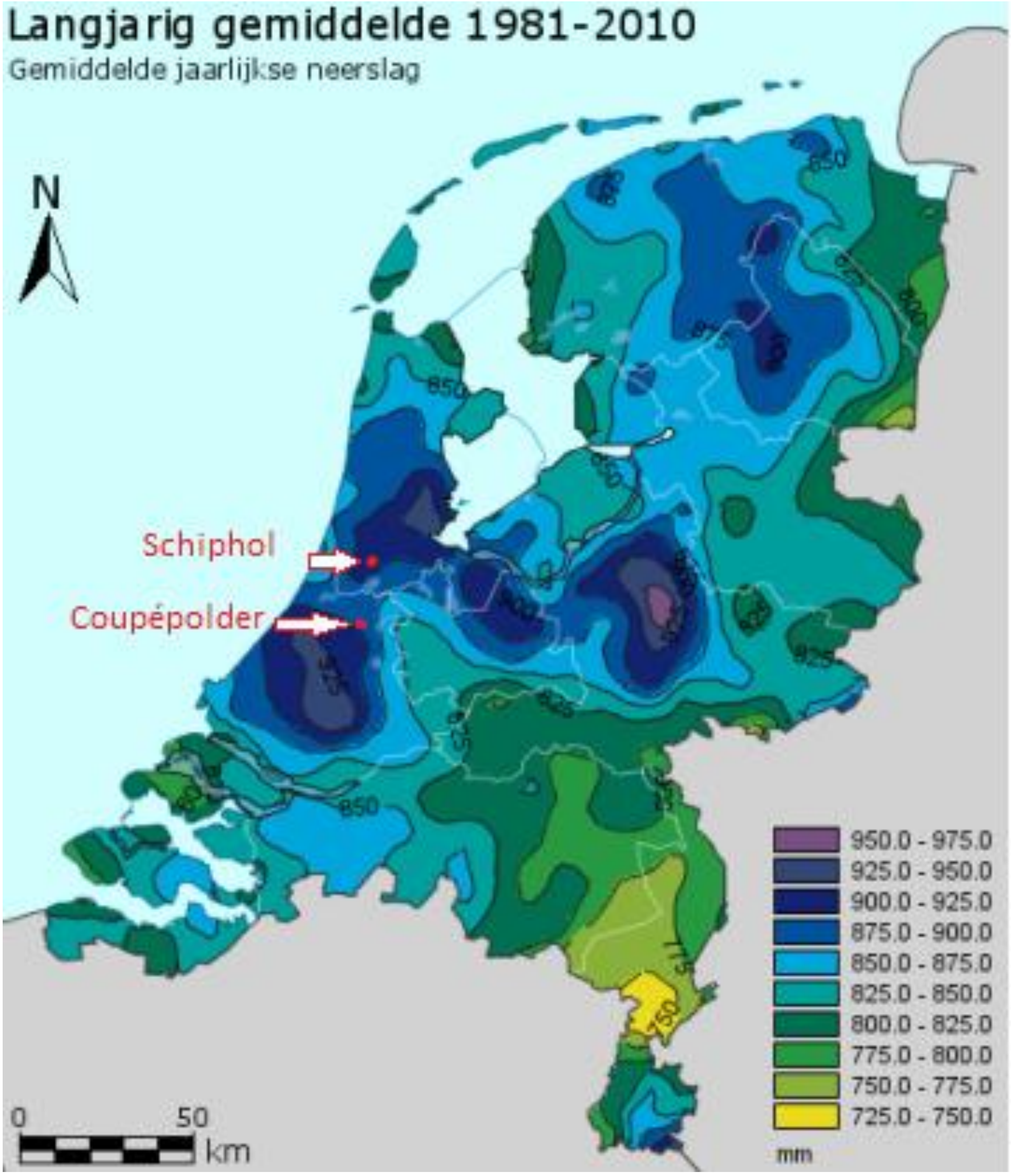
701*10^-6=7.01*10^-4 m2

7.01*10^-4*3802^2=10133m2 drainage area. (5.36 percent of total area).



## 9. Spatial variation in climatic mean rainfall in the Netherlands.

Source: KNMI.nl, 2010, Climatic mean rainfall of the Netherlands 1981-2010



## 11. Surface measurements using the Google Earth polygon tool

Adapted from google / aerodata international surveys 2014.