memo

To : Erik Mosselman
From : Jaap Kwadijk
Subject : scenarios voor binnenvaart
Date : 13 October, 2009
Cc :
Action:

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# Introduction

An unobstructed inland navigation is essential for the Rotterdam Harbour. Decreasing discharges in the Rhine and Meuse branches may lead to longer periods with low water levels. This may hamper the navigation. In this memo, estimates are made for changes in intensity and duration for low flow conditions due to climate change.

# Climate scenarios

In 2006, the Royal Netherlands Meteorological Institute (KNMI) presented four new climate scenarios for the Netherlands (Van den Hurk et al., 2006). These scenarios are based on a range of emission scenarios of five different General Circulations Models (GCMs). Due to the grid size between 200 and 500 km, the scenarios derived for the Netherlands also apply to the main part of the Rhine basin in Germany, with the exception of the Swiss Alps. For sub continental scale basins like the Rhine basin, the spatial resolution and the frequency statistics of a GCM become inadequate for forcing a hydrological model and downscaling is required. Regional climate models (RCMs) with an average resolution of 50 km are nested within GCMs and provide more regional detail without an unreasonable increase in computing time (Kay et al., 2006). The suite of RCM simulations used for the KNMI'06 climate scenarios is produced in the context of the European PRUDENCE project (Christensen et al., 2007; Lenderink, Van Ulden, et al., 2007). In PRUDENCE dynamical downscaling was applied using 10 RCMs and 3 GCMs, all run for two 30-year time slices: a control period 1960-1990 and a future period 2070-2100. Projected changes for 2050 result from linear interpolation between these dates. The simulation results show variable changes in projected strength of westerly winds in the area around the Netherlands. A strong change in atmospheric circulation is expected to result in milder and wetter winters due to more westerly winds, when compared to scenarios without atmospheric circulation change. Hence, both temperature and changes in the atmospheric circulation is used as steering parameters to discriminate four climate change scenarios Figure 0.1.

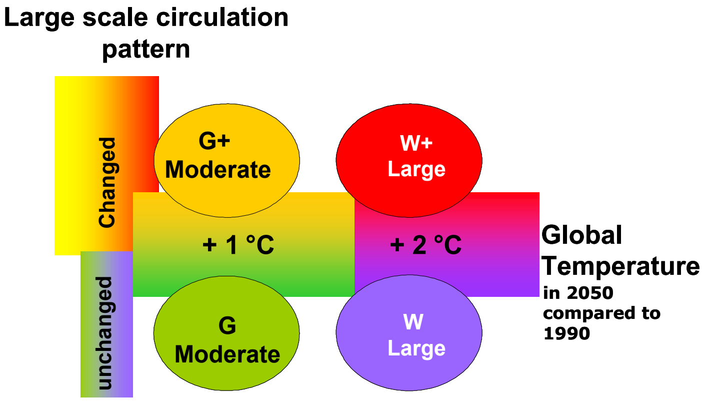


**Figure 0.1 The four KNMI 2006 scenarios.**

Deltares

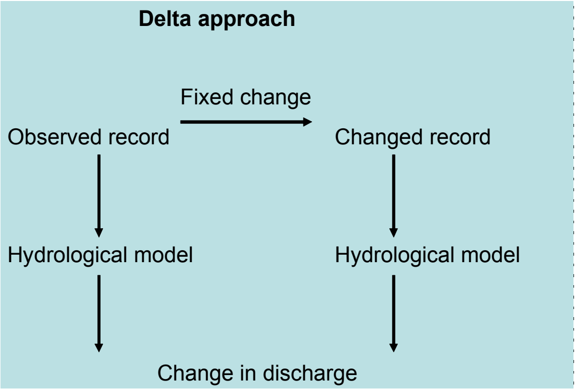
The KNMI’06 scenarios are summarized in Table 0.1 and describe a plausible range of possible future climate conditions, based on best available knowledge, and come without a statement on differences in probability between the scenarios. The KNMI scenario’s provide uniform scenario’s for the whole Rhine basin, not taking into account possible geographical differences in the change of precipitation and temperature.

| | G | G+ | W | W+ |
|---|---|---|---|---|
| **summertime** | | | | |
| mean temperature (K) | 0.9 | 1.4 | 1.7 | 2.8 |
| 10% warmest days (K) | 1 | 1.8 | 2 | 3.6 |
| 10% coldest days (K) | 0.9 | 1.1 | 1.8 | 2.2 |
| mean precipitation (%) | 2.8 | -9.5 | 5.5 | -19 |
| wet day frequency (%) | -1.6 | -9.6 | -3.3 | -19.3 |
| mean precipitation on wet day (%) | 4.6 | 0.1 | 9.1 | 0.3 |
| median of wet day precipitation (%) | -2.5 | -6.2 | -5.1 | -12.4 |
| precipitation on 0.01 wettest days (%) | 12.4 | 6.2 | 24.8 | 12.3 |
| | | | | |
| **wintertime** | | | | |
| mean temperature (K) | 0.9 | 1.1 | 1.8 | 2.3 |
| 10% warmest days (K) | 0.8 | 1 | 1.7 | 1.9 |
| 10% coldest days (K) | 1 | 1.4 | 2 | 2.8 |
| mean precipitation (%) | 3.6 | 7 | 7.3 | 14.2 |
| wet day frequency (%) | 0.1 | 0.9 | 0.2 | 1.9 |
| mean precipitation on wet day (%) | 3.6 | 6 | 7.1 | 12.1 |
| median of wet day precipitation (%) | 3.4 | 7.3 | 6.8 | 14.7 |
| precipitation on 0.01 wettest days (%) | 4.3 | 5.6 | 8.6 | 11.2 |

**Table 0.1Changes in the main climate parameters accroding to the KNMI 2006 scenarios for 2050**

# Projection of climate scenarios on the Rhine river basin

We constructed specific climate scenarios for the Rhine basin by applying the delta change approach on a historical data set of daily precipitation and temperature for the period 1961 – 1995. In the delta approach the future changes in the relevant climatic parameters (the 'deltas') are taken from a one of the four KNMI'06 climate scenarios. The differences (deltas) are used to transform historically observed climatic time series into possible future time series. Those transformed series are then used to drive a hydrological model that is calibrated to the characteristics of the river basin of interest.



This method adds the projected temperature increase to the observed temperatures. Evaporation and precipitation are perturbed by a fraction. KNMI provided average decadal (10 day) values of changes (so 36 values cover a year) in precipitation and temperature for all climate change scenarios for the year 2050.

Scenario temperature this calculated as

$$T_{scen,t',(x,y)} = T_{obs,t,(x,y)} + d\overline{T}_{scen,t}$$

Where

- $T_{\text{scen, t', (x,y)}}$ = the scenario temperature in decade t' in future on location (x,y) ($^{o}$C )
- $T_{\text{obs t, (x,y)}}$ = the observed temperature at t (x,y).
- $dT_{\text{scen, t}}$ = the average temperature chnage in that decade according one of the KNMI 2006 scenarios ($^{o}$C)

Scenario precipitation is calculated as:

$$P_{scen,t',(x,y)} = P_{obs,t,(x,y)} * \overline{P}_{scen,fractie,t}$$

Where :

- $P_{\text{scen, t'(x,y)}}$ = scenario preciptiation neerslag on location (x,y) for t' in future (mm);
- $P_{\text{obs 61-90, (x,y)}}$ = The observed precipitation sum at t on location (x,y), (mm);
- $P_{\text{scen, fractie,m}}$ = the mean change (fraction) in precipitation for that decade according to one of the KNMI scenarios (-).

Changes in Evaporation are calculated accordingly.

# Simulation of discharge

The delta method to produce climate scenario's based on the historical 1961-1995 climate series and the KNMI 2006 scenario's was used generate input series for P, T and Ep. These were used to run the RHINEFLOW-3 model as well as the HBV model.

All models of RHINEFLOW family are grid-based spatial water balance model. The models are often used for impacts of climate change on water availability in larger river basins (> 30,000 km2). RHINEFLOW-1, the parent model of this family, is a waterbalance model used for simulating the impact of climate change on the runoff regime of the river Rhine (Kwadijk, 1993; van Deursen and Kwadijk, 1993).

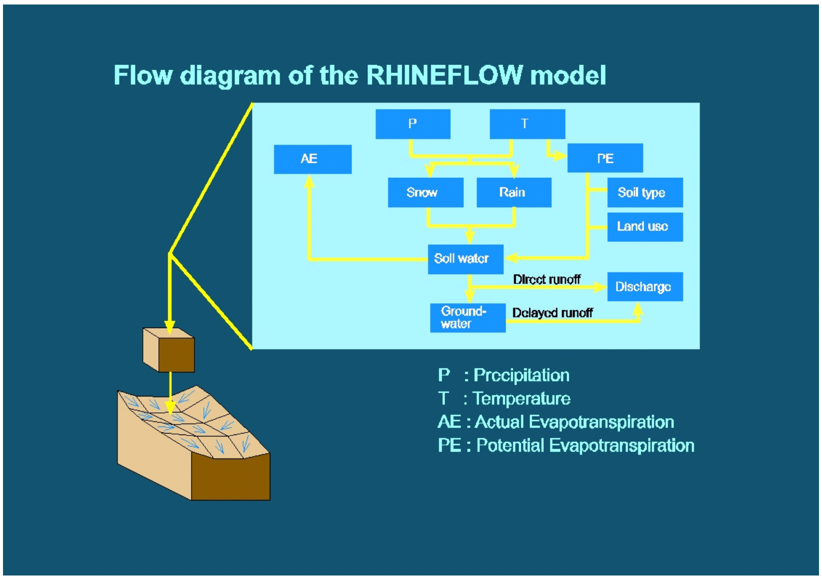


**Figure 0.1 Flow diagram of the Rhinflow model.**

The spatial water balance model in the RHINEFLOW model is based on a raster GIS calculating the water balance for each grid cell of the river. The direction of water flow is determined by a digital elevation model (DEM). In RHINEFLOW-1, the water balance is calculated using a temperature index model for snow fall and snow melt and 2 buckets representing the soilwater storage and the groundwater storage. The Thornthwaite & Mather (1957) equation is used for calculation of the potential and actual evaporation. This equation uses temperature and precipitation as the major input variables. It calculates actual evaporation depending on land use, actual soil moisture. The model runs on a monthly basis generating direct runoff, delayed runoff, groundwater storage (shallow and deep), snow water equivalents and snow melt.

HBV is a soil moisture accounting model that is used in the operational forecasting system of the river Rhine. It calculates the runoff on a daily basis. The land-phase of the hydrological cycle is represented by three different components: a snow routine, a soil routine and a runoff response routine. The snow routine is a temperature-index model that takes into account re-freezing. The incoming water from the snow routine is available for infiltration in the soil routine. The soil layer has a limited capacity to hold soil water, which means if this is exceeded the abundant water cannot infiltrate and, consequently, becomes directly available for runoff. Part of the infiltrating water will runoff through the soil layer (seepage). This runoff volume is related to the soil moisture content. The volume of water which becomes available for runoff is transferred to the runoff response routine. In this routine the runoff delay is simulated through the use of a number of linear reservoirs. Three types of runoff are distinguished: Quick runoff, Interflow and Slow runoff (baseflow)

# Results

## *Average changes in discharge at Lobith*

Similar to the application of the delta method for climatic time series, the delta method can also be used to circumvent or correct for biases encountered in the hydrological model; i.e. the (discharge) results from the hydrological model are not used directly but the changes in the discharge characteristics simulated by the hydrological model are used to adapt the historically observed discharge characteristics. The thus derived average changes in 10-day discharge volumes are used to perturb the historical daily discharge serie at Lobith for 1901-2004 via

$$Q_{scen} = Q_{obs} + (Q^{*}_{scen} - Q_{cntrl})$$

Where

- $Q_{scen}$ = the scenario discharge (m3/s)
- $Q_{obs}$ = the observed discharge (m3/s) in decade t
- $Q^{*}_{scen}$ = the average future discharge according to the model simulation (m3/s)
- $Q_{cntrl}$ = the average discharge according to the model simulation for the current climate conditions (base line) (m3/s)

In this way we derived scenario series of daily discharges for all 4 scenarios. These series were statistically analysed on changes in frequency, intensity and duration of dry spells.

## *Changes in the critical discharge for navigation.*

In this project the request was to generate a series for the 2004 discharge for the W+ scenario for 2050. Additionally we provide the 90 and 95% percentiles as these are critical discharges for navigation. The table below shows the average 1901-2004 monthly discharge discharges, the discharge for 2004 and the 10 / 90 % percentiles.

| month | average (1901-2004) | 2004 | 90% percentile | 10% percentile |
|---|---|---|---|---|
| jan | 2771 | 3188 | 4334 | 1447 |
| feb | 2725 | 2483 | 4294 | 1397 |
| mar | 2658 | 1687 | 4107 | 1487 |
| apr | 2481 | 1720 | 3822 | 1522 |
| may | 2229 | 1996 | 3091 | 1449 |
| jun | 2241 | 1992 | 3053 | 1562 |
| jul | 2137 | 1628 | 2820 | 1448 |
| aug | 1843 | 1492 | 2568 | 1151 |
| sep | 1694 | 1469 | 2487 | 1085 |
| oct | 1662 | 1502 | 2557 | 990 |
| nov | 1973 | 1915 | 3100 | 989 |
| dec | 2368 | 1634 | 3765 | 1337 |

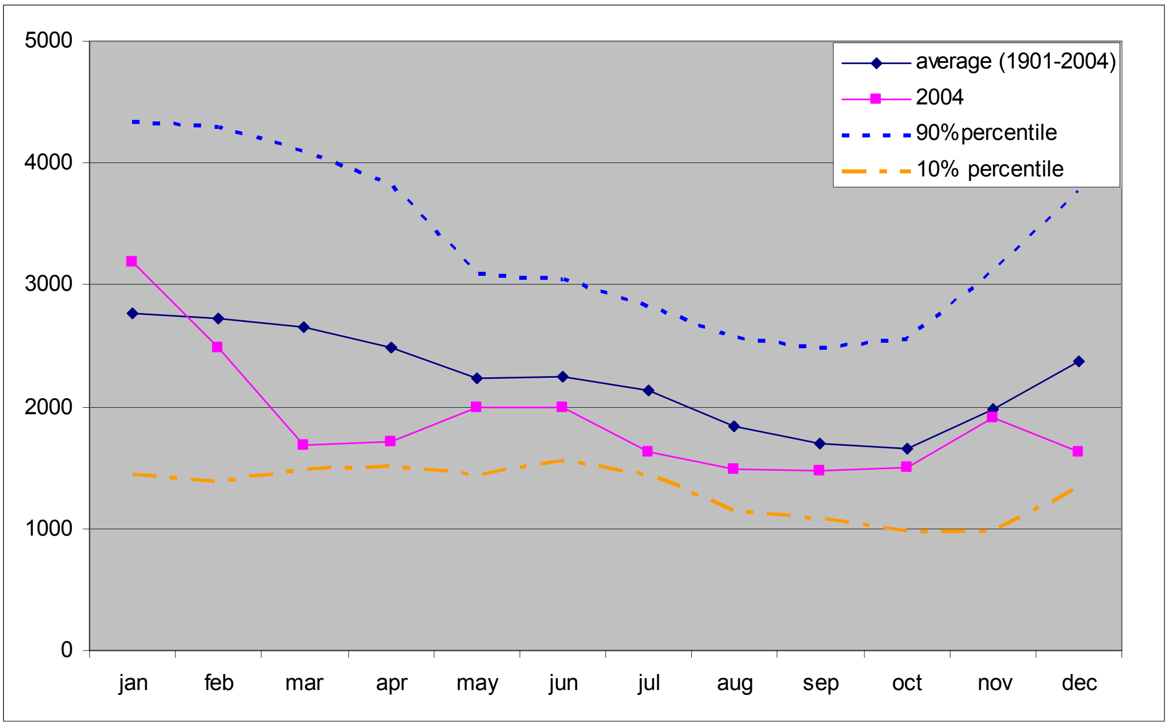


Figure xx shows that 2004 is a somewhat dryer than average

The table below shows the monthly discharges for 2004 as projected for 2050 assuming W+ climatic change.

| Month | 2004<br>current | 2004<br>W+ 2050 |
|---|---|---|
| 1 | 3188 | 3647 |
| 2 | 2483 | 2934 |
| 3 | 1687 | 1956 |
| 4 | 1720 | 1926 |
| 5 | 1996 | 2030 |
| 6 | 1992 | 1758 |
| 7 | 1628 | 1225 |
| 8 | 1492 | 977 |
| 9 | 1469 | 921 |
| 10 | 1502 | 1012 |
| 11 | 1915 | 1564 |
| 12 | 1634 | 1677 |

Both the Rhineflow as the HBV model show very comparable results for the projected 90 and 95% percentiles.

| | | (1901-2004) | G2050 | G+2050 | W2050 | W+2050 |
|---|---|---|---|---|---|---|
| Rhineflow | 90% percentiel | 1150 | 1185 | 1018 | 1210 | 864 |
| | 95% percentiel | 1000 | 1028 | 876 | 1051 | 735 |
| | | (1961-1990) | | | | |
| HBV | 90% percentiel | 1089 | | | 1164 | 885 |
| | 95% percentiel | 926 | | | 1025 | 776 |

## *Discharge and water level changes in Ruhrort and Kaub*

For Ruhrort and Kaub the changes for 2050 are based on the results of the study WL|Delfthydraulics, 2006, Effect of climate change on the rivers Rhine and Meuse, opsteller Aline te Linde. Opdrachtgever Rjkswaterstaat RIZA.

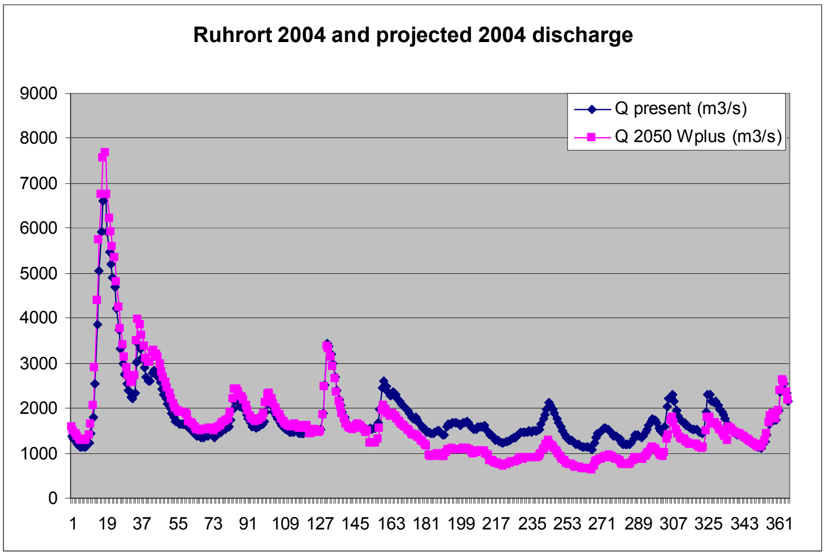
In this study, the KNMI 2006 scenarios for 2050 are projected on the river Rhine. The hydrological response in simulated using the HBV model in the FEWS-ED system. Simulations were made for daily discharges for the period 1961-1990 and scenario discharges were genereated as described earlier.

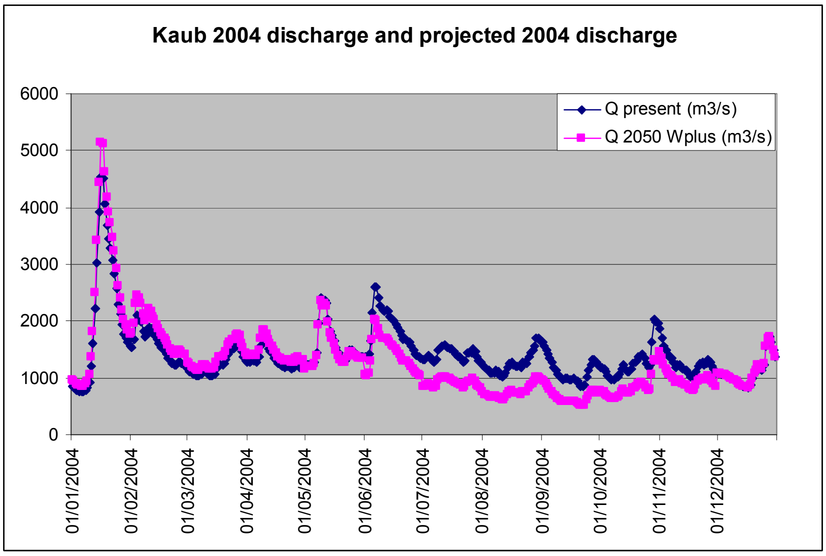
As the Ruhrort station was not specifically analysed, I used the changes for the Lobith gauging station. No major tributaries enter the Rhine between Ruhrort and Lobith. Therefore the error that is introduced can be considered small.

Table xx shows the average %-changes in monthly discharge for both stations

| | Kaub | | Ruhrort (Lobith) | |
|---|---|---|---|---|
| Month | W | Wp | W | Wp |
| Jan | 15.27 | 13.57 | 14.26 | 14.06 |
| Feb | 13.83 | 16.52 | 12.51 | 16.20 |
| Mar | 6.46 | 10.78 | 5.87 | 11.09 |
| Apr | 5.53 | 9.74 | 5.09 | 9.73 |
| May | 1.76 | -2.21 | 2.45 | -1.33 |
| Jun | -4.42 | -22.24 | -2.76 | -20.58 |
| Jul | -7.59 | -35.47 | -5.58 | -34.61 |
| Aug | -4.73 | -39.75 | -3.49 | -39.83 |
| Sep | -1.22 | -40.14 | -0.28 | -41.41 |
| Oct | 1.54 | -34.61 | 2.66 | -36.12 |
| Nov | 5.73 | -21.77 | 6.68 | -22.23 |
| Dec | 12.39 | 0.63 | 12.35 | 1.41 |

The discharges were transferred to water levels by applying the current stage/discharge relation of the stations.




Kaub 2004 discharge and projected 2004 discharge
6000
5000
4000
3000
2000
1000
0
Q present (m3/s)
Q 2050 Wplus (m3/s)
01/01/2004
01/02/2004
01/03/2004
01/04/2004
01/05/2004
01/06/2004
01/07/2004
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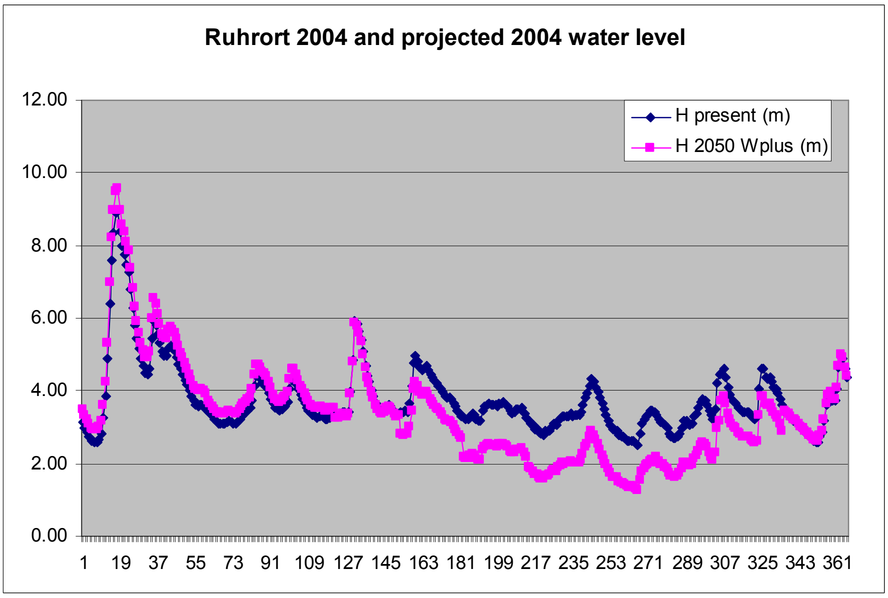
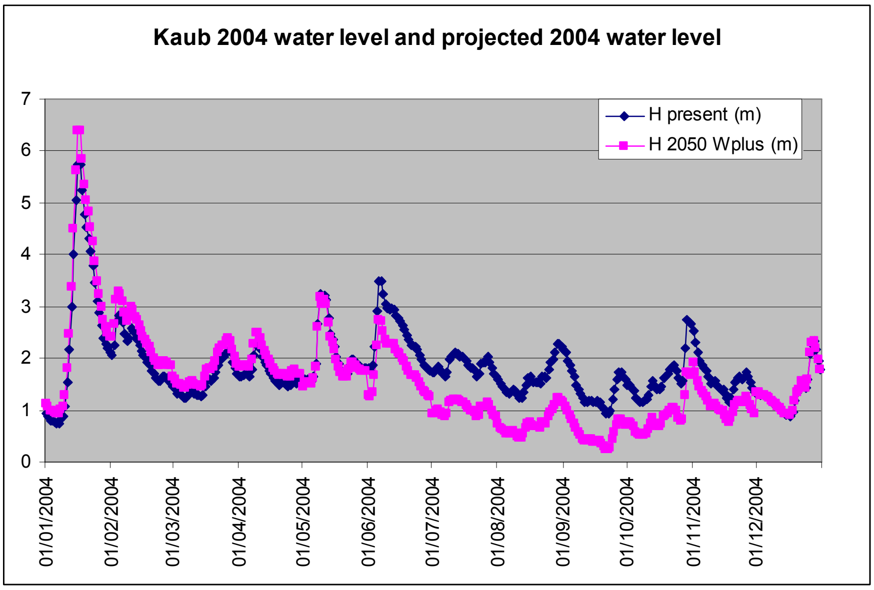
01/11/2004
01/12/2004


Ruhrort 2004 and projected 2004 water level
12.00
10.00
8.00
6.00
4.00
2.00
0.00
H present (m)
H 2050 Wplus (m)
1
19
37
55
73
91
109
127
145
163
181
199
217
235
253
271
289
307
325
343
361


Kaub 2004 water level and projected 2004 water level
7
6
5
4
3
2
1
0
H present (m)
H 2050 Wplus (m)
01/01/2004
01/02/2004
01/03/2004
01/04/2004
01/05/2004
01/06/2004
01/07/2004
01/08/2004
01/09/2004
01/10/2004
01/11/2004
01/12/2004