



**User's Guide**

**KALMAN-IN- WAQUA**





# User's Guide

## KALMAN-IN- WAQUA

A TIME (IN)VARIANT KALMAN FILTER IN  
WAQUA/TRIWAO

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# Contents

<b>1</b>	<b>ABOUT THIS MANUAL .....</b>	<b>5</b>
<b>2</b>	<b>GENERAL INFORMATION.....</b>	<b>7</b>
2.1	Features.....	7
2.2	Parameter types.....	9
2.3	Computational methods.....	11
2.4	Data Flow.....	19
2.4.1	Input.....	19
2.4.2	Output.....	19
2.5	Kalman programs.....	20
<b>3</b>	<b>WAQPRE WITH KALMAN.....</b>	<b>21</b>
3.1	kalman_histories .....	21
3.2	Restarts.....	22
<b>4</b>	<b>WAQPRO WITH KALMAN .....</b>	<b>23</b>



# 1 About this Manual

The User's Guide describes the Kalman subsystem of WAQUA/TRIWAQ, which is based on Simona tools and routines. WAQUA and TRIWAQ forecasts can be improved by using a time dependent or time independent Kalman filter, or boundary conditions can be calibrated.

This document is written for users who wish to use the Kalman filter in WAQUA or TRIWAQ models and is an extension to the User's Guide WAQUA. The user should be familiar with running WAQUA or TRIWAQ forecasts.

This User's Guide consists of four sections. Section 1 is this section. Section 2 gives General Information about the Kalman subsystem. In section 3 the simulation input for WAQPRE-with-Kalman is described. Section 4 is a quick reference guide for WAQPRO-with-Kalman, in which only additional information to the standard guide for WAQPRO is given.



## 2 General information

Using a Kalman filter, data can be assimilated in WAQUA/TRIWAQ models. Data assimilation can be useful in numerous applications. Whenever boundary conditions or wind forcing is not accurately known, a positive impact of assimilation can be expected. Especially storm surge predictions with large scale models can be improved tremendously using the Kalman filtering technique.

The filter type may be time independent (steady state) or time dependent (RRSQRT). The steady state filter is computed by KALMAN, using linearised flow computations, or by the RRSQRT filter.

The RRSQRT filter is fully integrated in WAQUA/TRIWAQ (optional). Each time step is repeated a number of times with different disturbances, thus very time consuming, but more flexible.

### 2.1 Features

The Kalman filter provides a stochastic approach to tidal predictions using on line measurements. WAQUA/TRIWAQ predictions are corrected in order to adapt the model to changing physical circumstances using waterlevel or velocity measurements. Uncertain parameters can be defined for wind noise, boundary conditions, and/or vertical eddy viscosity (TRIWAQ).

There are two options to perform Kalman filtering: by using a time dependent or a time independent filter.

#### time independent filter 1

In order to avoid a lot of computational effort the Kalman filter is approximated by a time invariant one, the steady state filter, as developed by A.W. Heemink ("Storm surge prediction using Kalman filtering", Rijkswaterstaat communications 46/1986). Using the time invariant approach the filter equations are solved only once, off line, resulting in the steady state filter gain. In this case the filter does not have to be computed each time a measurement becomes available. When the filter gain is computed, WAQUA predictions can be improved by using this filter during the WAQUA forecast.

**restrictions**

This time invariant filter is based on two-dimensional linearised shallow water equations. These linearised equations are basic equations suited for models using spherical co-ordinates only. Furthermore, the friction term in the model equations is also linearised. Horizontal advection and viscosity are neglected. Dryfall is not taken into account in the filter equations. However, the model may contain computational points which can fall dry during the WAQUA forecast. Computational grid points with a depth value smaller than zero (above mean sea level) do not take part in the Kalman filter computation and will therefore not be filtered during the WAQUA forecast. All other grid points will however be filtered during the WAQUA forecast, even if a point has temporarily fallen dry. Using this filter it is not possible to calculate WAQUA time integrals or WAQUA transport. It is also not possible to define movable barriers and weirs. This filter is only suited for in situ waterlevel data.

**time independent filter 2**

A second way to compute a time invariant Kalman gain is using the Reduced Rank Square Root algorithm (RRSQRT), as developed by M. Verlaan. Using this algorithm, the filter equations are again solved only once, resulting in a steady state filter gain. The gain is computed using the Kalman RRSQRT option in WAQUA/TRIWAQ, and is thus suited for 2D/3D models, (curvi-)linear or spherical models, including transport and the  $k-\epsilon$  turbulence model (3D). Measurement data may include waterlevels (in situ or satellite) and/or velocities (conventional or HF-radar).

**time dependent filter**

Since computational effort has increased a lot these days and computers are becoming faster every day, it is now possible to perform on line Kalman filtering. The time dependent filter is based on the RRSQRT (reduced rank square root) algorithm as developed by M. Verlaan ("Time varying Kalman filter for WAQUA"). Using the time varying approach the filter equations are solved on line during the WAQUA/TRIWAQ forecast, at every measurement time interval.

**restrictions**

The time dependent filter is based on the 2D/3D non-linear shallow water equations. The filter is suited for models using rectilinear, curvilinear or spherical co-ordinates. Furthermore, all WAQUA/TRIWAQ features such as horizontal advection and viscosity are taken into account by this filter.

## 2.2 Parameter types

At the current release, three types of parameters can be defined: wind noise, noise on vertical viscosity (3D) or boundary noise. The steady state filter of A.W.Heemink does not include 3D computations, and thus no noise on vertical viscosity.

### wind noise parameters

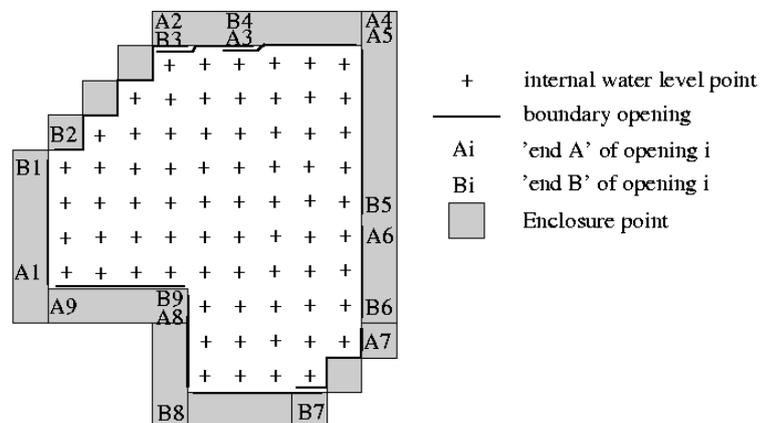
Wind noise parameters are defined at given wind grid points. This wind grid may be specified in a number of ways. The resulting wind grid is extended outside the WAQUA grid to ensure a complete overlap. In this way no WAQUA grid points will be left out during the filtering process. Wind noise can be added to the water velocities (output state) or to the wind stress (input forcing). In the steady state filter of A.W.Heemink wind noise can only be added to the output state.

### viscosity noise parameters

Vertical viscosity noise parameters (TRIWAQ) are defined the same as wind noise parameters, with the addition of the third dimension. The parameters in z-direction are defined at layer interfaces, starting at 0, with a fixed increment expressed as a multiple of layers.

### boundary noise parameters

Uncertain boundary parameters can only be defined for open boundaries. Open boundaries are defined in WAQUA through boundary openings with an 'A' end and a 'B' end as depicted in the figure below.



*Example of boundary openings. The openings 8-9-1-2-3-4-5-6-7 are all connected in various ways (Some overlap and some don't. Some connect 'end A' to 'end B' and some 'end A' to 'end A'. Some connect at an angle and some don't, etcetera)*

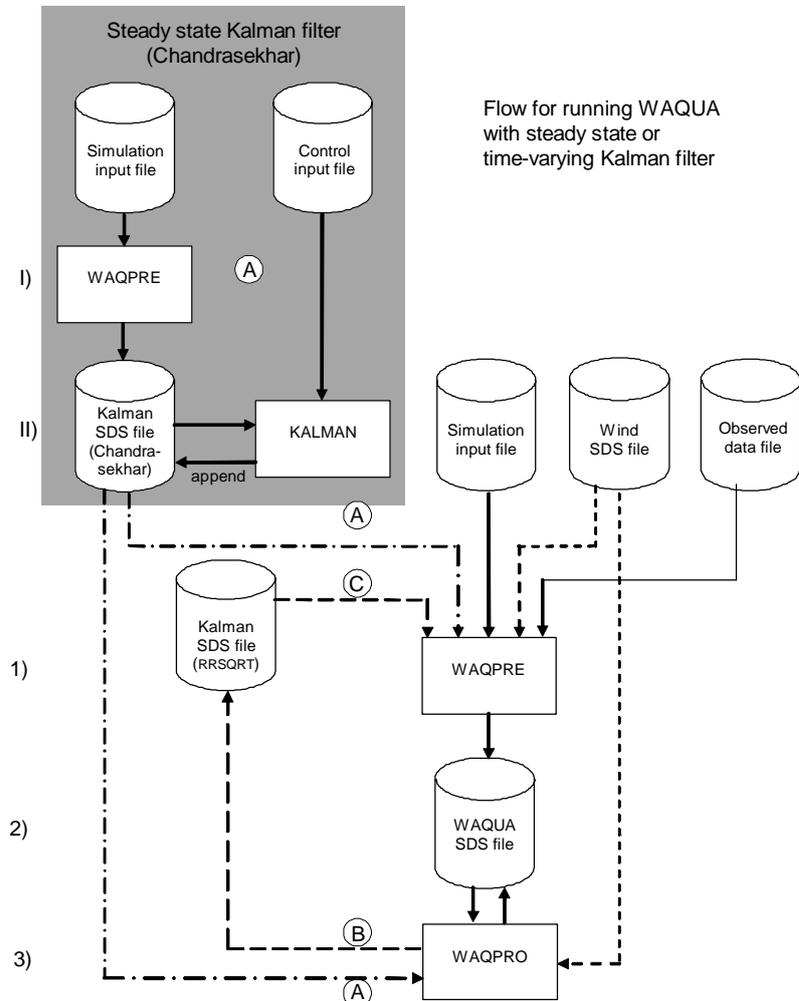
Uncertain boundary parameters can be defined at each 'A' or 'B' end. Boundary points representing a parameter are defined through line section pairs. A parameter is assigned to each of the outer ends of an input line pair. A single parameter point may be 'shared' by two line sections, if they connect and refer to compatible boundary conditions. The following table shows which boundary conditions are compatible.

<b>boundary condition</b>	<b>compatible to</b>
water levels	water levels
	qh-tables
velocities (u-direc)	velocities(u-direc)
velocities (v-direc)	velocities (v-direc)
discharges (u-direc)	discharges (u-direc)
	disch-ad (u-direc)
discharges (v-direc)	discharges (v-direc)
	disch-ad (v-direc)
Riemann invariants (u-direc)	Riemann invariants (u-direc)
Riemann invariants (v-direc)	Riemann invariants (v-direc)
disch-ad (u-direc)	discharges (u-direc)
	disch-ad (u-direc)
disch-ad (v-direc)	discharges (v-direc)
	disch-ad (v-direc)
qh-tables	water levels

The stochastic values at each open boundary point are obtained by B-spline interpolation [7], of which the order is free. Default is order 2 (two point = linear interpolation). When using an order >2, the interpolation will not cross "corners" in the open boundary. A corner is identified when two openings have a different direction.

## 2.3 Computational methods

**Program flow** The way to use either the steady state or the RRSQRT Kalman filter is depicted in the following program flow.



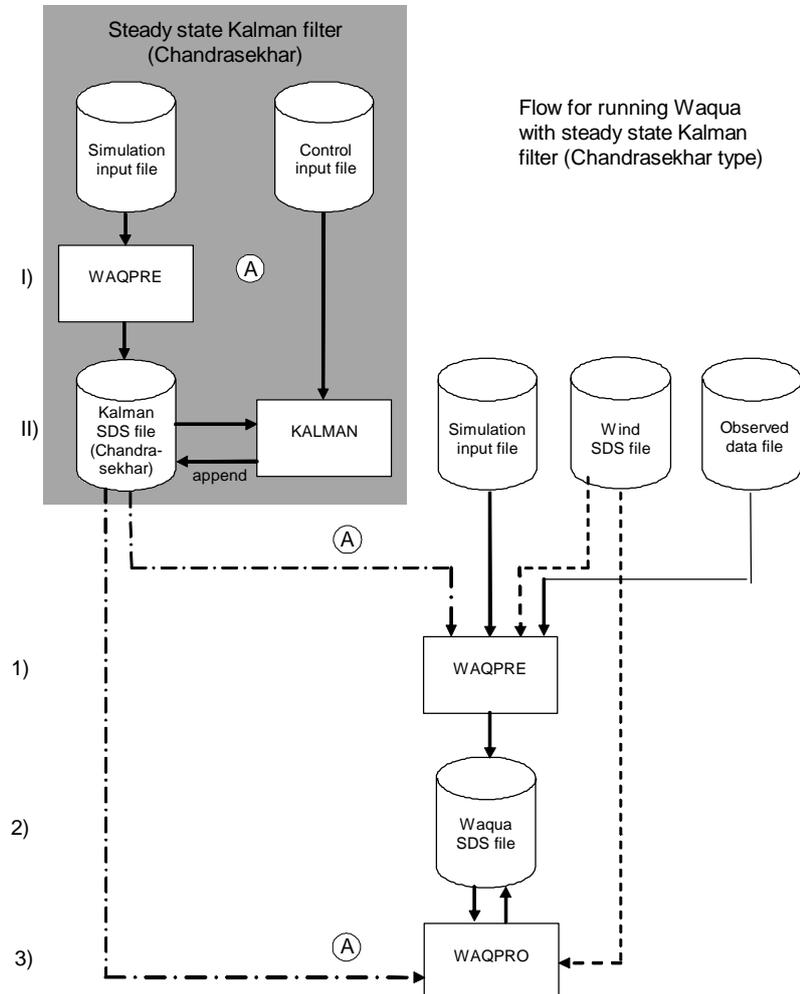
**(A)** in the flowchart concerns flows with respect to the steady state algorithm,  
**(B)** concerns flows with respect to the time dependent RRSQRT algorithm,  
**(C)** concerns flows with respect to the time independent filter, created with RRSQRT.

Which type of filter is to be used is decided by WAQPRE, depending on the user inputs in the simulation input file.

The program WAQPRE uses the program OBS2SDS to append the observed data to the WAQUA SDS file. See the user's guide for the program OBS2SDS for the description of the observed data input file.

**steady state algorithm  
(Chandrasekhar)**

**Time independent filter (Chandrasekhar)**



Using the Chandrasekhar type steady state algorithm, developed by A.W.Heemink, the Kalman filter gain is computed first, off line. The filter gain is calculated by the program KALMAN, of which the flow is given in the grey area of the flowchart. For more information on this calculation, the reader is referred to the User's Guide Kalman and the System Documentation of Kalman.

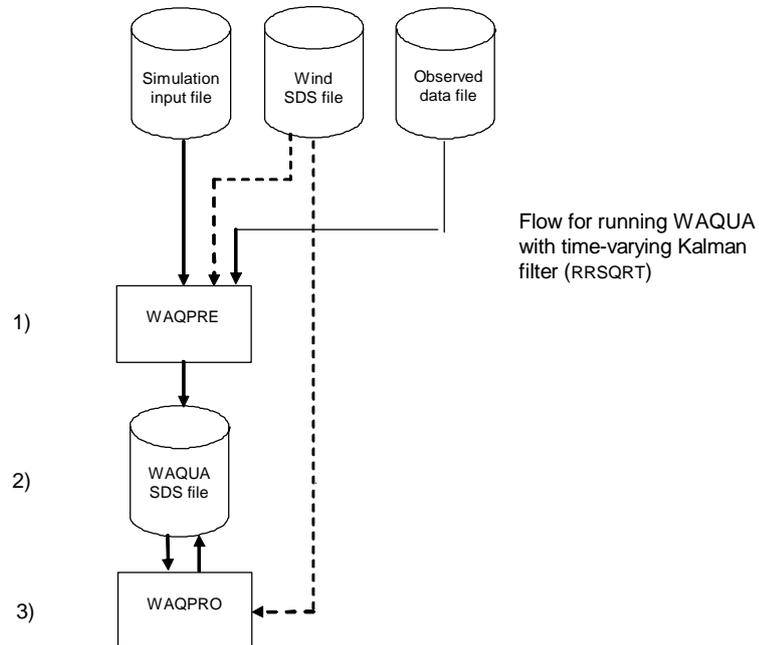
The steady state filter algorithm is activated in WAQUA by specifying the SDS file and experiment of the Kalman gain in the simulation input file of WAQUA. WAQPRE fills the Kalman-steady state part of the LDS and WAQPRO reads and uses the steady state gain.

After calculation of the filter gain, the WAQUA predictions are corrected. The correction steps resemble those of the time dependent filter, except for the Kalman time step and the Kalman reduction step:

- **WAQUA input:** Before a WAQUA time step is performed, coloured noise is added to the input forcing.
- **WAQUA time step:** After adding noise to the WAQUA input, a (whole) WAQUA time step is performed. The WAQUA state, consisting of velocities and water levels, are computed during this time step.
- **WAQUA output:** After the WAQUA time step, coloured noise is added to the u- and v-velocities of the WAQUA state when requested, since the wind parameters have affected the water velocities due to the wind stress.
- **Kalman measurement step:** After the WAQUA time step the Kalman measurement step is performed. The state that is calculated during the WAQUA time step is corrected using the steady state filter gain in combination with the available measurements.  
The measurement data can contain dummy values for missing observations.

## RRSQRT algorithm

## Time dependent filter



In order to use the RRSQRT algorithm, the corresponding control input must be specified in the simulation input file. WAQPRE fills the Kalman-RRSQRT part of the LDS and WAQPRO will use the time-dependent filter algorithm. When WAQPRO is finished, the resulting SDS-file contains the computed steady state gain(s), and can be used as Kalman SDS file in other WAQUA computations.

Using the RRSQRT algorithm, the WAQUA predictions are corrected, on line, following the next steps:

- **WAQUA input:** Before a WAQUA time step is performed, coloured noise is added to the forcing parameters.
- **WAQUA time step:** After adding noise to the WAQUA forcing (boundary noise, noise on wind stress), a (whole) WAQUA time step is performed. The WAQUA state, consisting of velocities, waterlevels, and transports, are computed during this time step.
- **WAQUA output:** After the WAQUA time step, coloured noise is added to the u- and v-velocities of the WAQUA state, when specified, since the wind parameters have affected the water velocities due to the wind stress.
- **Kalman time step:** (RRSQRT) The Kalman time step calculates the time propagation of the state estimate and error covariance and is equivalent to the Kalman filter equations described in the technical documentation TR02-08:

$$\hat{x}(k+1/k) = A(k)\hat{x}(k/k) + B(k)u(k)$$

$$L(k+1/k) = [A(k)L(k/k) F(k)\sqrt{\Sigma_s(k)}]$$

where:

- $\hat{x}(k/k)$  is the state estimate, a vector of dimension n
- $A(k)$  is the n by n system dynamics matrix
- $B(k)$  is the n by p noise input matrix
- $u(k)$  is a noise vector of dimension p
- $L(k/k)$  is the n by q estimate square root of the error covariance

The columns of L can be interpreted as error vectors in the state space. In some respect these columns are a generalisation of the 'modes' of a system and will therefore also be called modes.

- **Kalman reduction step:** (RRSQRT) The addition of rows,  $F(k)\sqrt{\Sigma_s(k)}$  for the system noise every time step would quickly increase the computational time. Therefore, the number of columns is reduced to q every time step. The concept of this approximation is to use only the first q eigenvalues and eigenvectors of the error covariance matrix. For a description of this reduction algorithm, the reader is referred to M. Verlaan ("Time varying Kalman filter for WAQUA").
- **Kalman measurement step:** The Kalman measurement step is performed at every measurement time interval. The state estimate, that is calculated during the Kalman time step, is now updated using the so-called measurement update equations (see M. Verlaan, "Time varying Kalman filter for WAQUA"). The measurement data are allowed to contain dummy values, which are ignored during the filtering process.
- **Optimisations:** (RRSQRT) Two options are available to optimise the Kalman computations. Both options concern the second part of L, containing the error vectors for each single parameter:
  - The time step for re-computation of these vectors can be set to a multiple of the WAQUA time step. It may even be set to infinite (that is, only compute once at the initial time step) in models approaching a linear flow, like CSM.
  - The Kalman computations can optionally be rearranged, resulting in zero error vectors for the state. These zeros will be skipped in the computations and will not be stored on disk. The more parameters, the

more optimising can be achieved with respect to computation time and disk space usage. When calibrating the Kalman parameters for a model, the results of computations with and without using zeros should be compared.

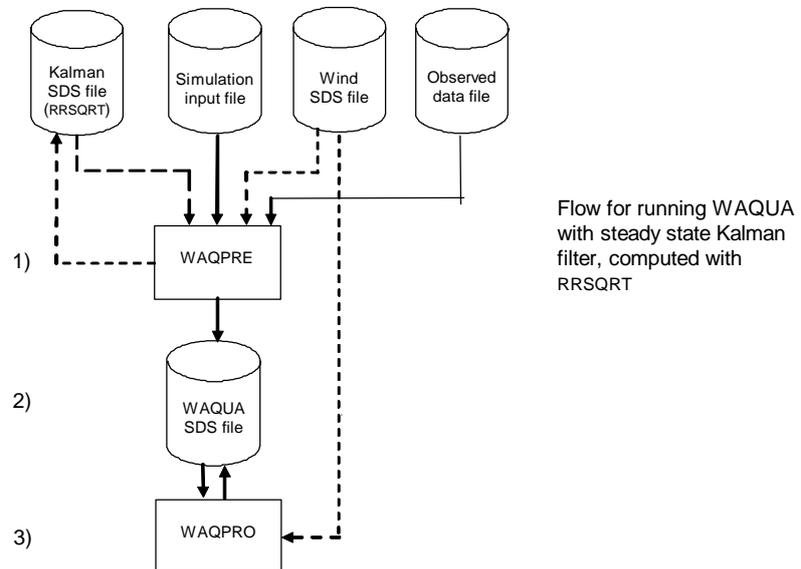
- **Additional features:**

- The smooth option

- When a boundary value is updated by the Kalman filter, it will take a while before this value reaches a certain measurement station. Once arrived at that station, it can be determined what the boundary value should have been in the past, in order to match the measurement as good as possible. This is the real value of interest, when Kalman is used to calibrate boundary parameters. For this purpose, the smooth option is introduced. Using this option, the maximum time period can be set for re-computing adaptations in the past. This results in new time series for the boundary values, which are saved on the SDS file, and can be read using the procedure "getser.pl". In order to save space, the times to write these results can be overridden by the user (default: the complete time range).

### steady state algorithm (RRSQRT)

### Time independent filter (RRSQRT)



Using the steady state gain, computed with RRSQRT, the Kalman filter gain is computed first by WAQUA-with-RRSQRT Kalman. A gain may have been computed at several time steps. The selected gain is copied to the WAQUA LDS by WAQPRE. After this step, the newly created SDS file can be used as a normal WAQUA SDS file, or can in turn be used as Kalman SDS file. The last mentioned option enables to reduce the size of the Kalman SDS file, as the original Kalman SDS file may contain several gains, map dat, history data, and so on.

The steady state filter algorithm is again activated in WAQUA by specifying the SDS file and experiment of the Kalman gain in the simulation input file of WAQUA, and additionally specifying the time step at which the requested gain was computed. The WAQUA predictions are corrected in the same way as described for the Chandrasekhar type filter algorithm, but with some additions:

- **WAQUA input:** Before a WAQUA/TRIWAQ time step is **performed**, coloured noise is added to the input forcing (boundary forcing or wind stress).
- **WAQUA time step:** After adding noise to the WAQUA input, a (whole) WAQUA/TRIWAQ time step is performed. The WAQUA state, consisting of velocities, water levels and transports, are computed during this time step.
- **WAQUA output:** After the WAQUA/TRIWAQ time step, coloured noise is added to the u- and v-velocities of the WAQUA state when requested, since the wind parameters

have affected the water velocities due to the wind stress. In 3D, coloured noise is also added to the vertical eddy viscosity when applicable.

- **Kalman measurement step:** After the WAQUA time step the Kalman measurement step is performed. The state that is calculated during the WAQUA/TRIWAQ time step is corrected using the steady state filter gain in combination with the available measurements. The measurement data can contain dummy values, since residuals (observation - prediction) are estimated by the Kalman filter during the prediction process in case a measurement is not available. However, it is not advisable that there are too many dummy values in the data, for all the corresponding residuals have to be estimated.
- **Additional features:**
  - The smooth option  
When the filter was computed with the smooth option, the gain also includes the boundary history. This enables the reconstruction of the boundary time series which can be read from the SDS file using the procedure "getser.pl".

## 2.4 Data Flow

### 2.4.1 Input

- siminp file** A simulation input file is required. Parameters for Kalman are specified in input chapter KALMAN (see section 3).
- Kalman SDS file** In case of a computation using a steady state Kalman filter, a Kalman SDS file is needed. It is created by the application KALMAN (refer to the User Guide Kalman) or by WAQUA -with-RRSQRT Kalman.
- Observed data file** In case of a computation using Kalman filtering (steady state or time dependent) a file with observed data is needed. This data must be appended to the SDS file by WAQPRE (which calls the program OBS2SDS). See the OBS2SDS user's guide for an explanation of the syntax of the observed data file.

### 2.4.2 Output

- SDS file** The SDS file is the standard output file of WAQUA/TRIWAQ. The LDS is extended with a Kalman section, which is described in the Technical Documentation, TR02-09.
- Error and warning messages** The batch programs print run, error and warning messages as applicable in the {program}-m.{runid} files.

## 2.5 Kalman programs

<b>Processor Kalman</b>	The Kalman processor computes a steady state filter gain, as developed by A.W.Heemink, and is described in User's Guide Kalman and the Technical Documentation in TR02-08 and TR02-09.
<b>pre-processor WAQPRE</b>	WAQPRE allows the specification of the Kalman option and processes the observed data file, by calling the program OBS2SDS.
<b>processor WAQPRO</b>	WAQPRO carries out the calculations.
<b>Post-processors</b>	Results can be presented using standard post-processing tools like BASISANALYSE and KALGUI.

### 3 WAQPRE with Kalman

The standard WAQUA pre-processor WAQPRE can be extended with the Kalman option. The input is described in the User's Guide WAQPRE.

When using a Kalman filtering technique, the simulation input file for WAQUA/TRIWAQ must be extended with one main key-word:

```

KALMAN
  |  STEADY_STATE
<
  |  RRSQRT
<
  |  OPENDA

```

Either one of the sub-key-words STEADY\_STATE, RRSQRT or OPENDA must be specified, and are described in the User's Guide WAQPRE.

In addition, when using the boundary smoothing option (RRSQRT), WAQUA's input paragraph "SDSOUTPUT" can be extended with sub-paragraph "KALMAN\_HISTORIES". See section 3.1.

#### 3.1 kalman\_histories

With the "smooth" option in the RRSQRT filter algorithm it is possible to reconstruct the boundary based on observed data. When this option is used, the new boundary values for the complete smooth time period is written to the SDS file at each computation time step by default. This is done when using the RRSQRT algorithm, as well as when using the steady state filter, computed with the RRSQRT algorithm.

With a small time step, this can result in a large amount of output data. For instance, consider the following input:

```

number of open boundary points:   nto = 65
time step:                        dtmin = 0.5 min.
smooth period:                    smooth = 100 min.

```

The array with the new boundary values for the complete smooth time period will be of size:

$$2 * nto * (smooth / dtmin + 1) = 2 * 65 * 201 = 26130 \text{ words.}$$

This array is default saved at each WAQUA time step. For one day, this leads to the following disk space needed just for the boundary history values:

$$\begin{aligned}
 (\text{minutes per day})/(\text{time step}) * 26130 &= 2880 * 26130 \\
 &\approx 75 \text{ Mw} \\
 &= 300 \text{ Mb}
 \end{aligned}$$

After three days, this results in an amount of approximately 1 Gb needed just for the history of the new boundary values!

In order to save disk space, alternative disk output can be specified. This is done in the input section SDSOUTPUT (refer to the User's Guide WAQUA).

```

SDSOUTPUT
  KALMAN_HISTORIES      (optional)
  TFKHISTORIES=[val]
  TIKHISTORIES=[val]
  TLKHISTORIES=[val]

```

#### Explanation:

- |                                     |   |
|-------------------------------------|---|
| <b>tfkhistor</b> ies = <i>[val]</i> | <b>d</b> Time in minutes relative to TSTART to start the storage of boundary history values (Time First).<br>Default = TSTART |
| <b>tikhistor</b> ies = <i>[val]</i> | <b>m</b> Time Interval in minutes to store the boundary history values.<br>Default = DTMIN                                    |
| <b>tlkhistor</b> ies = <i>[val]</i> | <b>d</b> Time in minutes relative to TSTART to end the storage of boundary history values (Time Last).<br>Default = TSTOP     |

**Notes:** Omitting the complete sub-section KALMAN\_HISTORIES will result in the storage of the complete time range

## 3.2 Restarts

When restarting a computation (see 'RESTART' in WAQPRE's users' manual), some of the KALMAN-inputs must be identical to the KALMAN-inputs of the original calculation:

- Value for SMOOTH
- Inputs for LINE\_SECTIONS
- Inputs for GRID of main keywords VISCOSITY\_NOISE and WIND\_NOISE
- Choice for STRESS in WIND\_NOISE
- Stations used for assimilation
- Value for NMODE
- Choice for RRSQRT or STEADY\_STATE

## 4 WAQPRO with Kalman

<b>Purpose</b>	<p>The WAQUA/TRIWAQ processor WAQPRO carries out the calculations. The Kalman option combines WAQUA's numerical approach to tidal predictions with a statistical approach in order to adapt the model to changing physical circumstances.</p> <p>This section only gives a quick reference for the usage of WAQPRO, as an extension to the quick reference guide in User's Guide WAQPRO.</p>	
<b>Data Flow</b>	<u>Input files</u> Simona data storage files	<u>Output files</u> Simona data storage file
<b>FileNames</b>	<u>Logical name</u> WAQUA SDS file Kalman SDS file (svw&p file)	<u>System name</u> SDS-<runid WAQUA> SDS-<runid Kalman> SDS-<runid WAQWND>
<b>File Description</b>	<u>Logical name</u> WAQUA SDS file  Kalman SDS file svw&p SDS file	<u>Purpose</u> Storage of permanent WAQUA - with Kalman data model data + Kalman gain space varying wind & pressure
<b>User's Guide</b>	See 'User's Guide WAQUA'	
<b>Test input</b>	Not yet available	
<b>Exceptions</b>	No integral computations allowed. Steady state filter of A.W.Heemink: only 2-dimensional spherical models without transport.	
<b>Format</b>	See 'User's Guide WAQUA'	
<b>Notes</b>	With respect to the user interface, the difference in running WAQUA with or without Kalman filter is only found in the simulation input file. The mechanism corresponds to that of activating space varying wind and pressure.	