Supplementary information

A Water balance model flux formulations

A.1 Parameter symbols, units, and descriptions

Symbol	Unit	Description
h_{sf}	L	Surface elevation relative to mean sea level
h	L	Groundwater level relative to mean sea level
s_p	L	Surface water level outside catchment relative to mean sea level
s	L	Surface water level relative to mean sea level
p	L	Field surface water level relative to mean sea level
t	T	Time
P	L^3	Precipitation
E	L^3	Reference evaporation (Makkink)
f_p	-	Evaporation reduction factor, specified per month
f_{pc}	-	Evapotranspiration reduction factor, specified per month
A_l	L^2	Surface area land
A_w	L^2	Surface area water
F_{si}	L	Fixed seepage or infiltration (lower boundary)flux
K_v	LT^{-1}	Subsurface conductivity of peat/clay cover layer
d	L	Thickness of cover layer
h_d	L	Water pressure lower boundary (below peat/clay cover layer)
ϕ	-	Porosity
g	LT^{-2}	Accelleration of gravity (≈9,8 m/s^2)
m	-	Discharge coëfficiënt
b	L	Width of weir
SG	L^3	Storage in groundwater domain
SG_{ex}	L^3	Storage in groundwater domain excluding inundation flux (FL_g)
SL	L^3	Storage in field surface domain
SL_{ex}	L^3	Storage in field surface domain excluding inundation flux (FL_g)
SS	L^3	Storage in surface water domain
SS_{ex}	L^3	Storage in surface water domain excluding inlet and outlet (FS_{in} en

		FS_{out})
f_l	-	Fraction of groundwater volume that exfiltrates to surface water per unit difference between groundwater and surface water level
f_r	-	Fraction of surface water volume that infiltrates to groundwater per unit difference between surface water and groundwater level
f_i	-	Fraction of groundwater volume that inundates to the field surface per unit difference between groundwater and field surface water level
f_{of}		Fraction of field storage volume that flows to surface water (via overland flow) per unit difference between field surface water level and field surface elevation.
f_{b_in}	-	Fraction of surface water volume that infiltrates (leaks) from outside the catchment to the groundwater storage per unit difference between surface water level outside the catchment and the groundwater level within the catchment
f_{b_uit}		Fraction of groundwater volume that exfiltrates (leaks) to surface water outside the catchment per unit difference between the groundwater level within the catchment and the surface water level outside the catchment.
S_{min}	L	Minimum surface water level relative to mean sea level (start inlet)
S_{max}	L	Maximum surface water level relative to mean sea level (start outlet)
FS_{outmax}	L	Maximum pumping capacity for outlet

A.2 Fluxes groundwater domain

In (positive) or out (negative) fluxes

FG_{PE}	Flux to and from groundwater through precipitation and evapotransipration
FG_{ri}	Exchange between groundwater domain and deep groundwater through seepage (r) or infiltration (i)
FG_{leak}	Exchange between groundwater domain and surroundings (leakage through catchment boundaries)

In fluxes

FG_{I}	Flux to groundwater from field storage (infiltration from ponds)
FG_{s}	Flux to groundwater from surface water (surface water infiltration)

Out fluxes

FS_{g}	Flux to surface water from groundwater (exfiltration)
FL_{g}	Flux to field storage from groundwater (inundation from groundwater)

Formulas:

FG_{PE}	Flux to and from groundwater through precipitation and evapotransipration

$$If: (h_{(t-1)} < h_{sf})$$
$$Then: \{FG_{PE} = (P_{(t)} - E_{(t)} \cdot f_{pc}) \cdot A_{i}\}$$
$$Else: \{ If: (p_{(t-1)} - h_{sf} < -(P_{(t)} - E_{(t)} \cdot f_{p}))$$
$$Then: \{FG_{PE} = ((P_{(t)} - E_{(t)} \cdot f_{p}) - (h_{sf} - p_{(t-1)})) \cdot f_{pc} \cdot A_{i}\}$$
$$Else: \{FG_{PE} = 0\}$$
$$\}$$
$$\}$$

FG_{ri}	Exchange between groundwater domain and deep groundwater through seepage (r) or infiltration (i)

Seepage (positive) / infitration (negative):
Choice between fixed flux or fixed head boundary.

- For fixed flux

$$FG_{ri} = F_{ri} \cdot A_{i}$$

- For fixed head:

$$FG_{ri} = K_{v} \cdot \frac{h_{d} - h_{(t-1)}}{d} \cdot A_{i}$$

FG_{leak}	Exchange between groundwater domain and surroundings (leakage through catchment boundaries)

$$FG_{leak} =$$
$$If (h_{(t-1)} > h_{p})$$
$$Then: (s_{p} - h_{(t-1)}) \cdot f_{b\_uit} \cdot \phi \cdot A_{i}$$
$$Else: (s_{p} - h_{(t-1)}) \cdot f_{b\_in} \cdot A_{i}$$

FG_l	Flux to groundwater from field storage (infiltration from ponds)

$$If: (h_{(t-1)} < h_{sf}) AND (p_{(t-1)} > h_{sf})$$

$$Then: \{ If: (p_{(t-1)} - h_{sf}) < (h_{sf} - h_{(t-1)}) \cdot \phi + FL_{PE} \cdot A_l^{-1}$$

$$Then: \{FG_l = (p_{(t-1)} - h_{sf}) \cdot A_l + FL_{PE} \cdot A_l\}$$

$$Else: \{ FG_l = (h_{sf} - h_{(t-1)}) \cdot A_l \cdot \phi\}$$

$$\}$$

$$Else: \{FG_l = 0\}$$

FG_s	Flux to groundwater from surface water (surface water infiltration)

$$If: (s_{(t-1)} < h_{(t-1)})$$

$$Then: \{FG_s = 0\}$$

$$Else: \{IF: (s_{(t-1)} - h_{(t-1)}) \cdot f_r \cdot A_w > (s_{(t-1)} - h_{(t-1)}) \cdot \phi \cdot A_l$$

$$Then: \{FG_s = (s_{(t-1)} - h_{(t-1)}) \cdot \phi \cdot A_l\}$$

$$Else: \{FG_s = (s_{(t-1)} - h_{(t-1)}) \cdot f_r \cdot A_w\}$$

$$\}$$

FS_g	Flux to surface water from groundwater (exfiltration)

$$If: (s_{(t-1)} > h_{(t-1)})$$

$$Then: \{FS_g = 0\}$$

$$Else: \{ FS_g = (s_{(t-1)} - h_{(t-1)}) \cdot f_l \cdot \phi \cdot A_l\}$$

Storage change in groundwater domain excluding inundation flux:

$$\partial SG_{ex} = FG_{PE} + FG_{ri} + FG_{leak} + FG_s + FG_l - FS_g$$

FL_g	Flux to field storage from groundwater (inundation from groundwater)

$$If: (h_{(t-1)} + \partial SG_{ex} \cdot A_l^{-1} \cdot \phi^{-1} < h_{sf})$$

$$Then: \{FL_g = 0\}$$

$$Else: \{ FL_g = (h_{(t-1)} + \partial SG_{ex} \cdot A_l^{-1} \cdot \phi^{-1} - h_{sf}) \cdot f_i \cdot A_l \cdot \phi\}$$

Storage change in groundwater domain:

2 calculations possible

$$\partial SG = FG_{PE} + FG_{ri} + FG_{leak} + FG_s + FG_l - FS_g - FL_g = \partial SG_{ex} - FL_g$$

$$\partial SG = (h_{(t)} \cdot A_l \cdot \phi) - (h_{(t-1)} \cdot A_l \cdot \phi)$$

Groundwater level:

$$\partial h = (\partial SG \cdot A_l^{-1}) \cdot \phi^{-1}$$

$$If: (h_{(t-1)} + \partial h > h_{sf})$$

$$Then: \{h = h_{sf}\}$$

$$Else: \{ h_t = h_{(t-1)} + \partial h\}$$

A.3 Fluxes field storage domain

In (positive) or out (negative) fluxes

FL_{pe}	Flux to and from field storage through precipitation and evapotransipration

In fluxes

FL_g	Flux to field storage from groundwater (inundation from groundwater)
FL_s	Flux to field storage from surface water (inundation from surface water)

Out fluxes

FS_l	Flux to surface water from field storage (overland flow)
FG_l	Flux to groundwater from field storage (infiltration from ponds)

Formulas:

FL_{pe}	Flux to and from field storage through precipitation and evapotransipration

$$
\begin{aligned}
&If: (h_{(t-1)} < h_{sf}) \\
&Then: \{FL_{PE} = 0\} \\
&Else: \{\, If: (p_{(t-1)} = h_{sf}) \text{ AND } (P_{(t)} < E_{(t)} \cdot f_p) \\
&\qquad Then: \{FL_{PE} = 0_l\} \\
&\qquad Else: \{If: (p_{(t-1)} - h_{sf} < -(P_{(t)} - E_{(t)} \cdot f_p)) \\
&\qquad\qquad Then: \{FL_{PE} = h_{sf} - p_{(t-1)} \cdot A_l\} \\
&\qquad\qquad Else: \{FL_{PE} = (P_{(t)} - E_{(t)} \cdot f_p) \cdot A_l\} \\
&\qquad\qquad \} \\
&\qquad \}
\end{aligned}
$$

FL_g	Flux to field storage from groundwater (inundation from groundwater)

See formulas groundwater domain

FS_l	Flux to surface water from field storage (overland flow)

$$
\begin{aligned}
&If: (p_{(t-1)} > h_{sf}) AND (s_{(t-1)} > p_{(t-1)}) \\
&Then: \{\, If: (p_{(t-1)} - h_{sf} < (h_{sf} - h_{(t-1)}) \cdot \phi) \\
&\qquad Then: \{FS_l = 0\} \\
&\qquad Else: \{If: ((p_{(t-1)} - h_{sf}) \cdot A_l - FG_l + FL_{pe}) \cdot f_{of} < 0) \\
&\qquad\qquad Then: \{FS_l = 0\} \\
&\qquad\qquad Else: \{FS_l = ((p_{(t-1)} - h_{sf}) \cdot A_l - FG_l + FL_{pe}) \cdot f_{of}\} \\
&\qquad\qquad \} \\
&\qquad \} \\
&Else: \{FS_l = 0\}
\end{aligned}
$$

FG_l	Flux to groundwater from field storage (infiltration from ponds)

See formulas groundwater domain

Storage change in field surface domain excluding inundation flux:

$$\partial SL_{ex} = FL_{PE} + FL_g - FS_l - FG_l$$

FL_s	Flux to field storage from surface water (inundation from surface water)

$$If: (s_{(t-1)} + (FS_{pe} + FS_{ri} + FS_g + FS_l - FG_s) \cdot A_w^{-1} < p_{(t-1)} + \partial SL_{ex} \cdot A_l^{-1})$$

$$Then: \{FL_s = 0\}$$

$$Else: \{(FL_s = s_{(t-1)} + (FS_{pe} + FS_{ri} + FS_g + FS_l - FG_s) \cdot A_w^{-1} - (p_{(t-1)} + \partial SL_{ex} \cdot A_l^{-1}) \cdot (A_l \cdot (A_l + A_w)^{-1}) \cdot A_l\}$$

Storage change in field surface domain:

2 calculations possible

$$\partial SL = FL_{PE} + FL_g + FL_s - FS_l - FG_l = \partial SL_{ex} + FL_s$$

$$\partial SL = (p_{(t)} \cdot A_l) - (p_{(t-1)} \cdot A_l)$$

Field surface water level:

$$\partial p = \partial SL \cdot A_l^{-1}$$

$$p_t = p_{(t-1)} + \partial p$$

A.4 Fluxes surface water domain

In (positive) or out (negative) fluxes

FS_{PE}	Flux to and from surface water through precipitation and evapotransipration
FS_{ri}	Exchange between surface water domain and deep groundwater through seepage (r) or infiltration (i)

In fluxes

FS_g	Flux to surface water from groundwater (exfiltration)
FS_l	Flux to surface water from field surface (overland flow)
FS_{in}	Flux from regional water system to surface water (inlet)

Out fluxes

FG_s	Flux to groundwater from surface water (surface water infiltration)
FL_s	Flux to field surface from surface water (inundation from surface water)
FS_{out}	Flux from surface water to regional water system via outlet
FS_{leak}	Flux from surface water to regional water system via leakage

Formulas:

FS_{PE}	Flux to and from surface water through precipitation and evapotransipration

$$FS_P = P_{(t)} \cdot A_w$$

$$FS_E = E_{(t)} \cdot f_p \cdot A_w$$

$$FS_{PE} = (P_{(t)} - E_{(t)} \cdot f_p) \cdot A_w = FS_P - FS_E$$

FS_{ri}	Exchange between surface water domain and deep groundwater through seepage (r) or infiltration (i)

Seepage (positive) / infitration (negative):
Choice between fixed flux or fixed head boundary.

- For fixed flux:

$$FS_r = F_r \cdot A_w$$

$$FS_i = F_i \cdot A_w$$

$$FS_{ri} = FS_r + FS_i$$

- For fixed head:

Infiltration:

$$IF: K_v \cdot \frac{h_d - s_{(t-1)}}{d} \cdot A_w > 0$$

$$Then: \{FS_i = 0\}$$

$$Else: \{FS_i = K_v \cdot \frac{h_d - s_{(t-1)}}{d} \cdot A_w\}$$

Seepage:

$$IF: K_v \cdot \frac{h_d - s_{(t-1)}}{d} \cdot A_w < 0$$

$$Then: \{FS_i = 0\}$$

$$Else: \{FS_i = K_v \cdot \frac{h_d - s_{(t-1)}}{d} \cdot A_w\}$$

FS_g	Flux to surface water from groundwater (exfiltration)

See formulas groundwater domain

FS_l	Flux to surface water from field surface (overland flow)

See formulas field surface domain

FG_s	Flux to groundwater from surface water (surface water infiltration)

See formulas groundwater domain

FL_s	Flux to field surface from surface water (inundation from surface water)

See formulas field surface domain

Storage change in surface water domain excluding inlet and outlet:

$$\partial SS_{ex} = FS_{PE} + FS_{ri} + FS_g + FS_l - FG_s - FL_s$$

FS_{in}	Flux from regional water system to surface water (inlet)

$$If: (s_{(t-1)} + \partial SS_{ex} \cdot A_w^{-1} > S_{\min})$$
$$Then: \{FS_{in} = 0\}$$
$$Else: \{IF: (S_{\min} - s_{(t-1)}) \cdot A_w - \partial SS_{ex} > FS_{inmax}$$
$$Then: \{FS_{in} = FS_{inmax}\}$$
$$Else: \{FS_{in} = (S_{\min} - s_{(t-1)}) \cdot A_w - \partial SS_{ex}\}$$
$$\}$$

FS_{out}	Flux from surface water to regional water system via outlet
FS_{leak}	Flux from surface water to regional water system via leakage

Three options::

1. No outlet and no leakage

   $$FS_{out} = 0$$
   $$FS_{leak} = 0$$

2. Outlet via pumping station and no leakage:

   $$If: (s_{(t-1)} + \partial SS_{ex} \cdot A_w^{-1} < S_{\max})$$
   $$Then: \{FS_{out} = 0\}$$
   $$Else: \{ If: (s_{(t-1)} - S_{\max}) \cdot A_w + \partial SS_{ex} > FS_{outmax}$$
   $$Then: \{FS_{out} = FS_{outmax}\}$$
   $$Else: \{FS_{out} = (s_{(t-1)} - S_{\max}) \cdot A_w + \partial SS_{ex}\}$$
   $$\}$$

   $$FS_{leak} = 0$$

3. Outlet via a weir, part of which can be attributed to leakage:

   $$If: (s_{(t-1)} < S_{\max})$$
   $$Then: \{FS_{out} = 0\}$$
   $$Else: \{ FS_{out} = (\frac{2}{3} \cdot \sqrt{(\frac{2}{3} \cdot g)} \cdot m \cdot b \cdot (s_{(t-1)} - S_{\max})^{1.5} \}$$

Storage change in surface water domain:

$$F_{in} = FS_{PE} + FS_{ri} + FS_{g} + FS_{l} + FS_{in}$$

$$F_{out} = FG_{s} + FL_{s} + FS_{out} + FS_{leak}$$

$$\partial SS = F_{in} - F_{out}$$

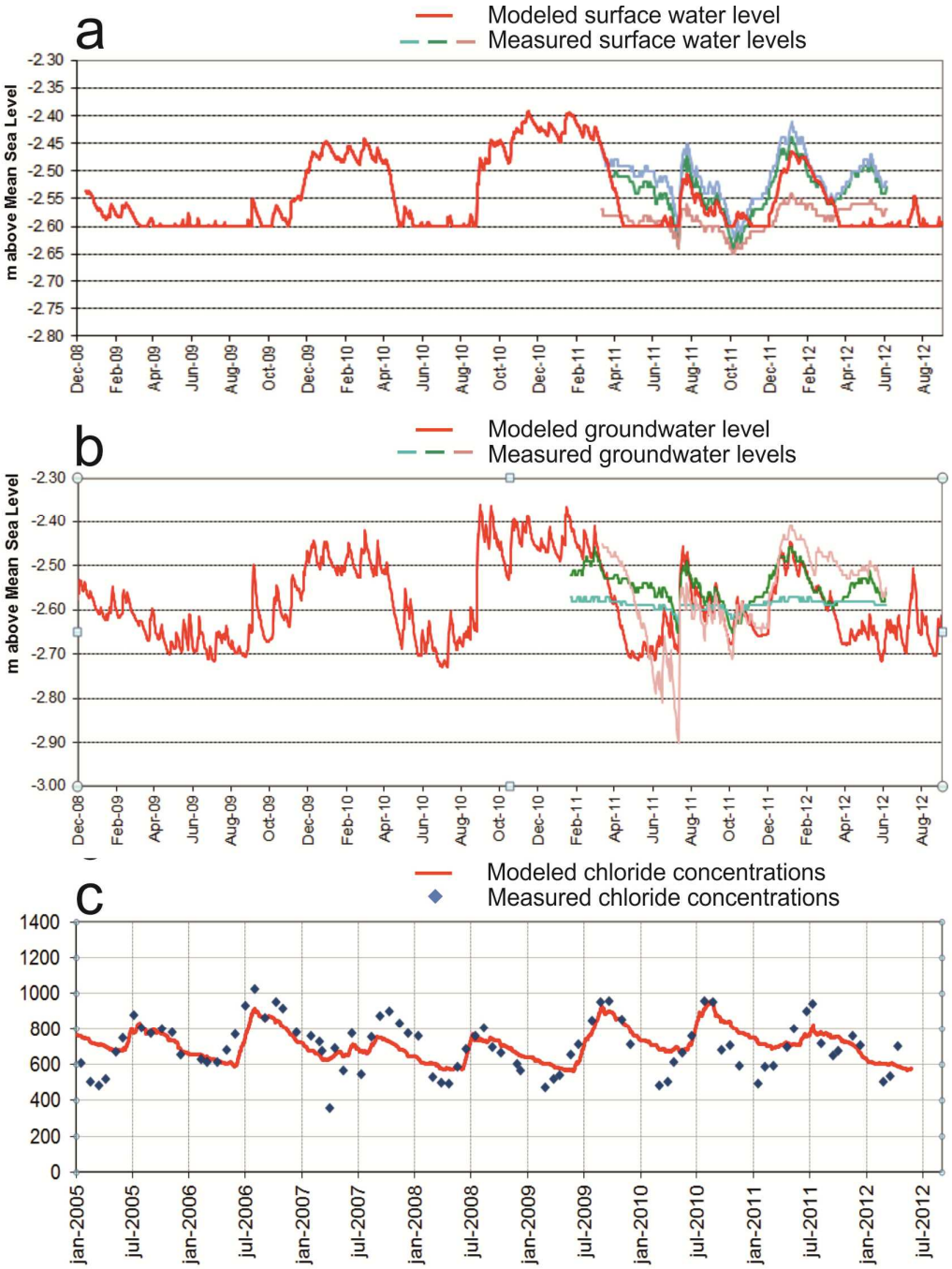
Surface water level:

$$\partial z = \partial SS \cdot A_{w}^{-1}$$

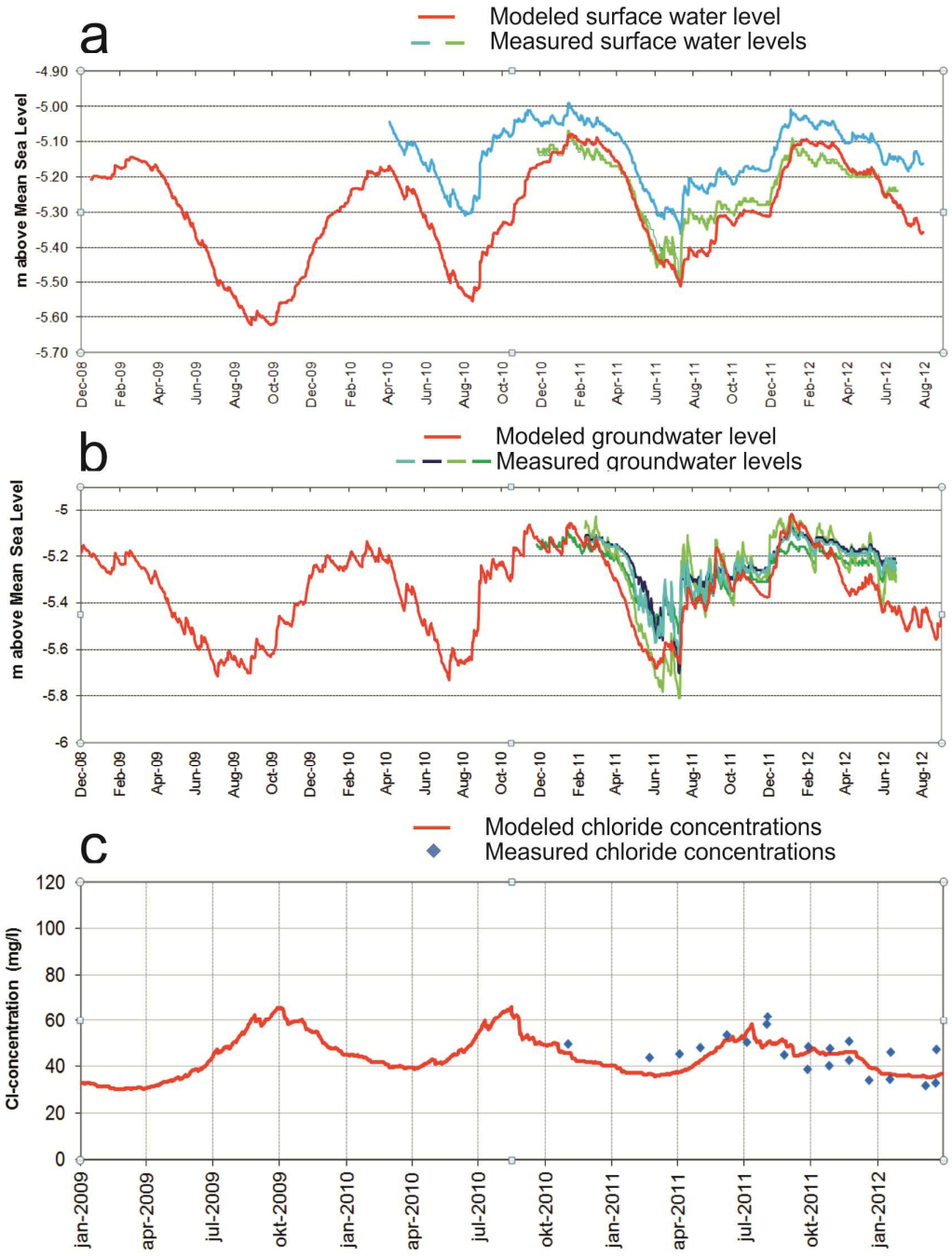
B Water balance model performance

Water balance model performance on simulating the surface water levels (a), groundwater levels (b), and chloride concentrations (c) for all studied polders.

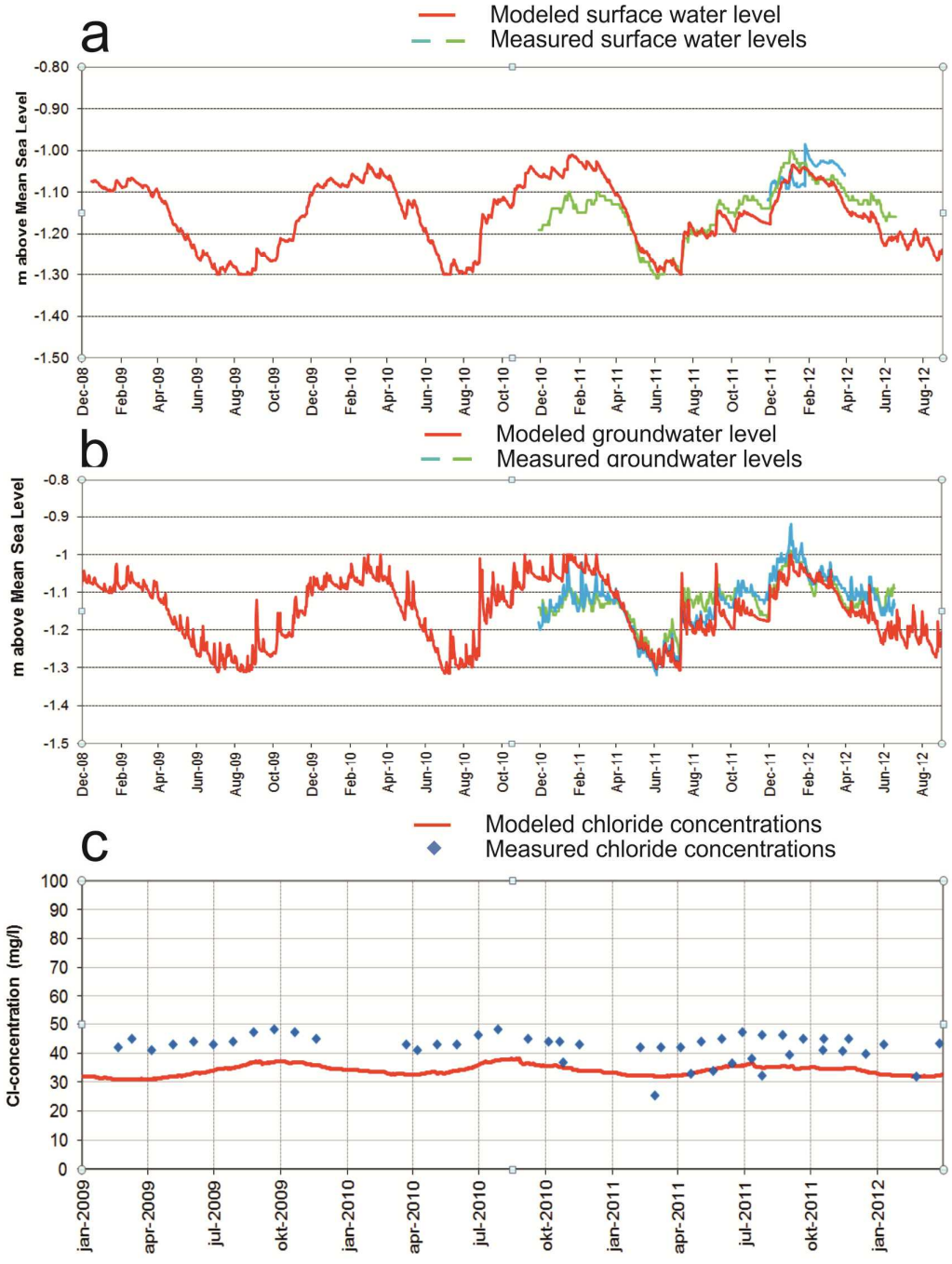
Botshol



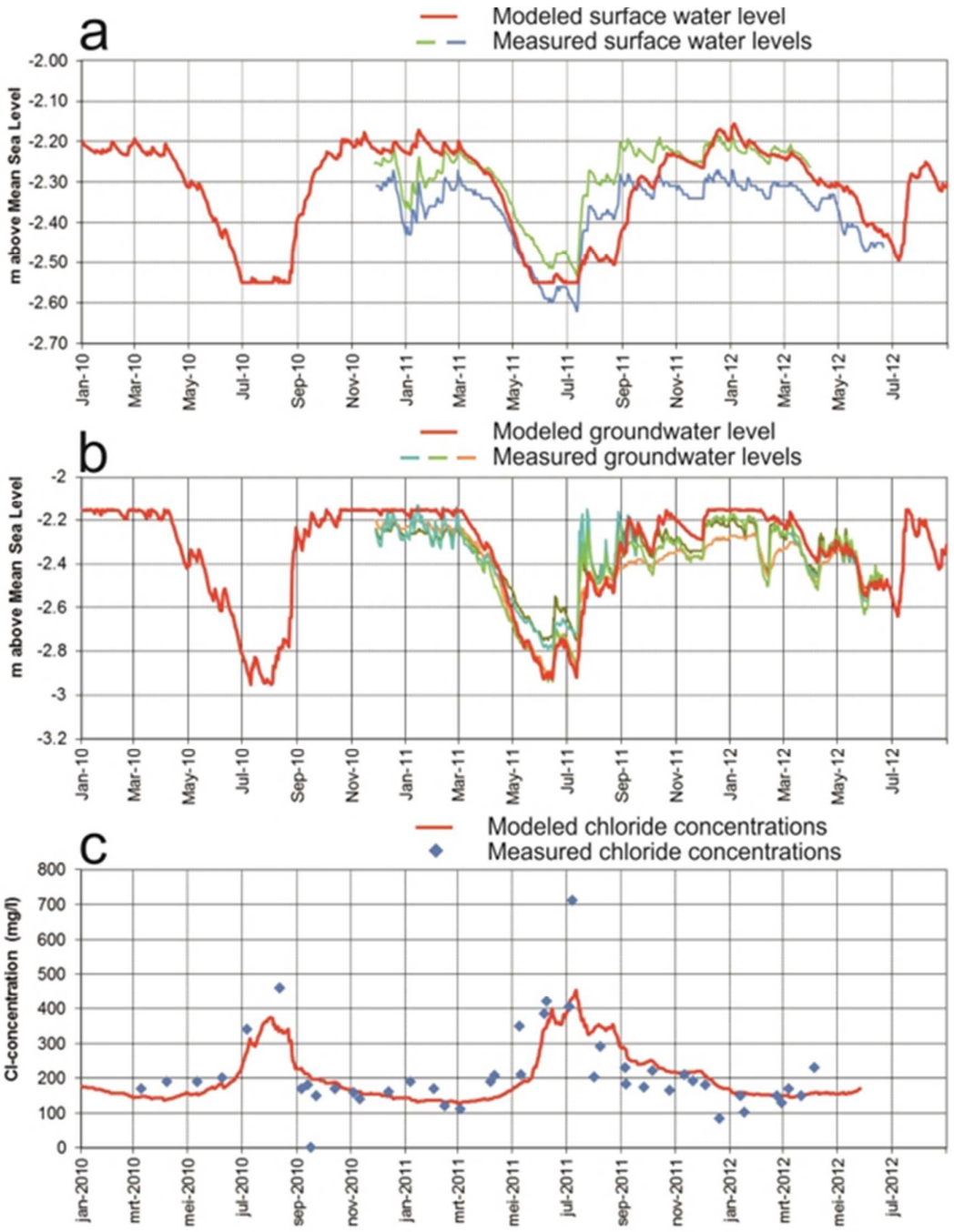
Groene Jonker



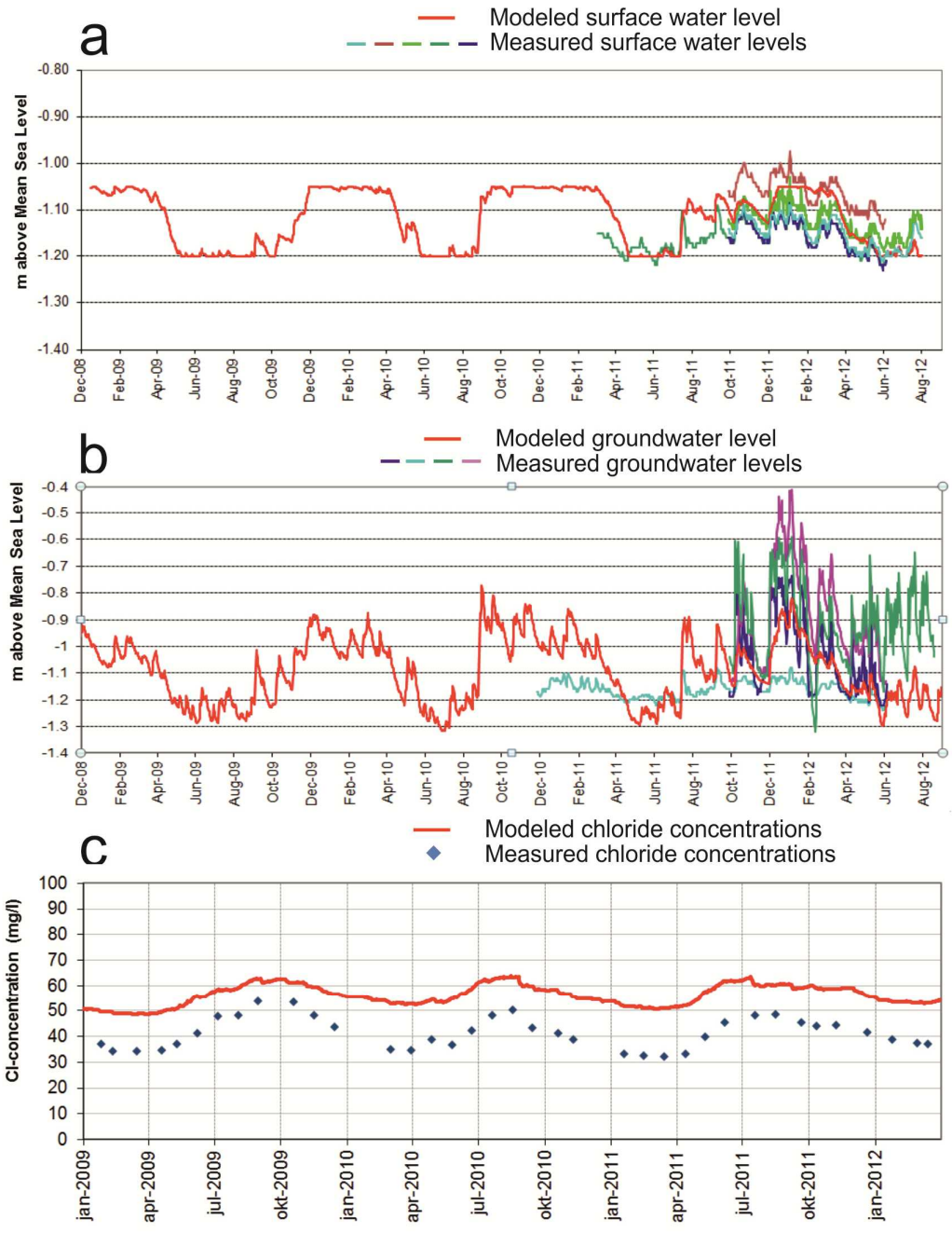
Loenderveen Oost



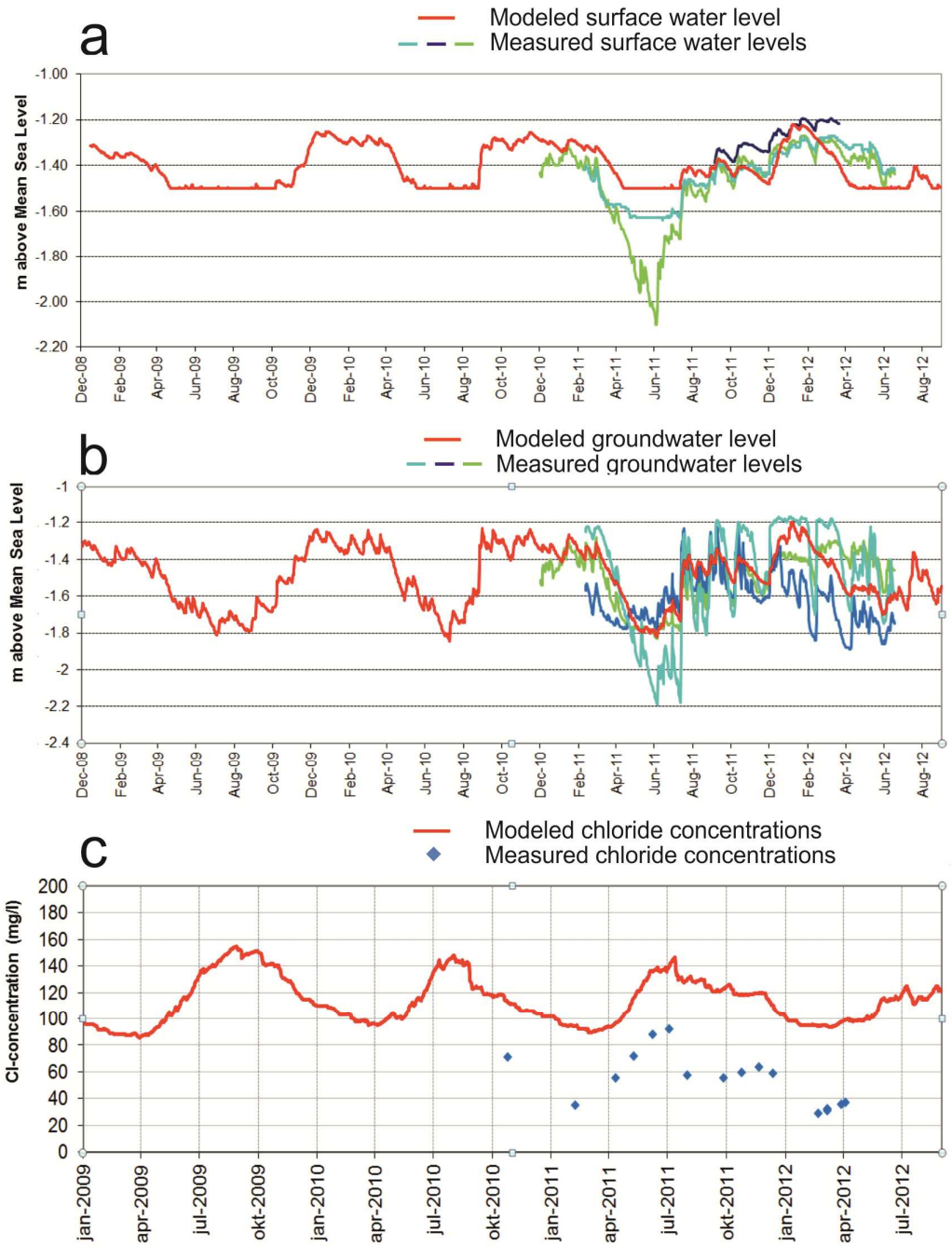
Middelpolder



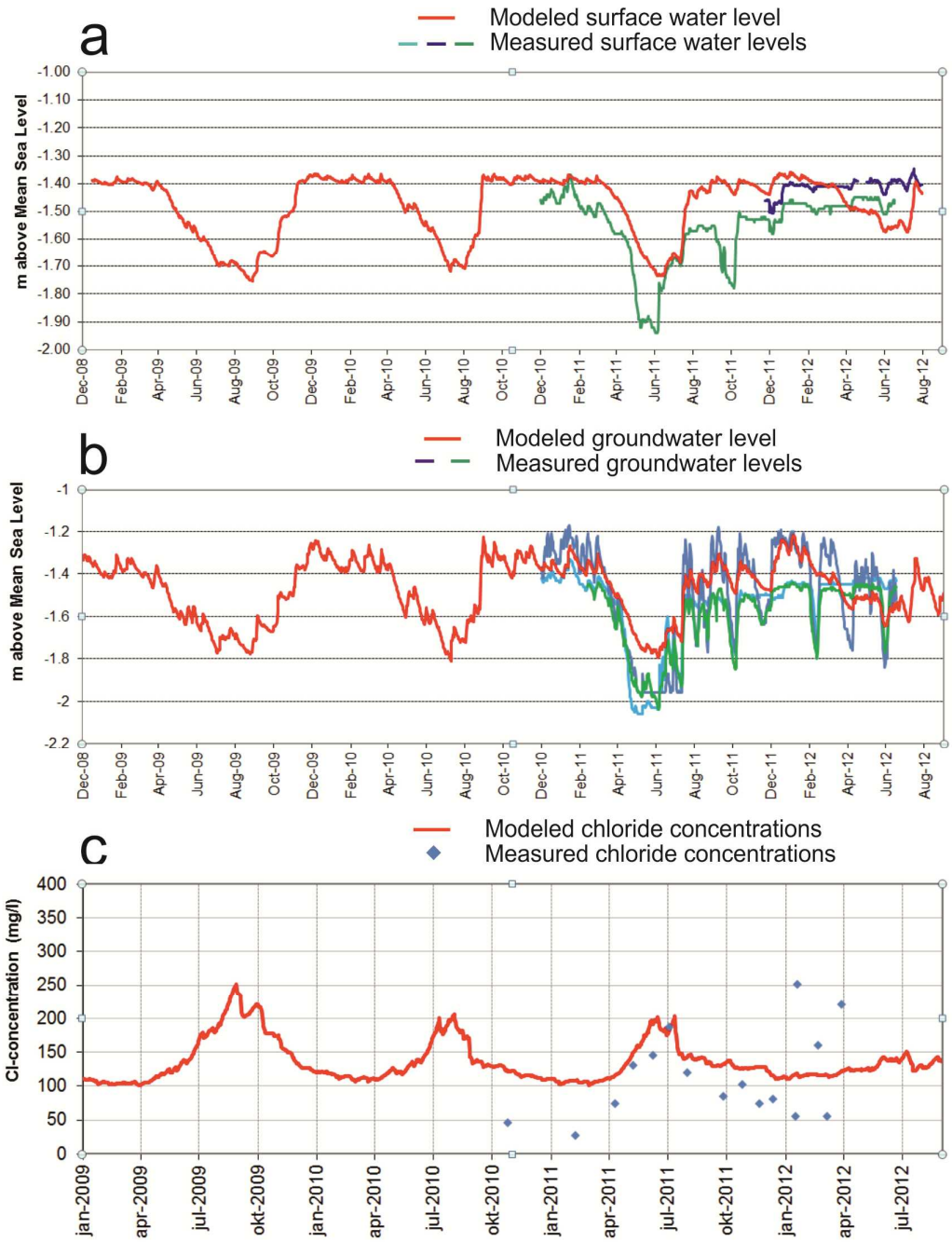
Muyeveld


a
Modeled surface water level
Measured surface water levels
m above Mean Sea Level
-0.80
-0.90
-1.00
-1.10
-1.20
-1.30
-1.40
Dec-08
Feb-09
Apr-09
Jun-09
Aug-09
Oct-09
Dec-09
Feb-10
Apr-10
Jun-10
Aug-10
Oct-10
Dec-10
Feb-11
Apr-11
Jun-11
Aug-11
Oct-11
Dec-11
Feb-12
Apr-12
Jun-12
Aug-12
b
Modeled groundwater level
Measured groundwater levels
m above Mean Sea Level
-0.4
-0.5
-0.6
-0.7
-0.8
-0.9
-1
-1.1
-1.2
-1.3
-1.4
Dec-08
Feb-09
Apr-09
Jun-09
Aug-09
Oct-09
Dec-09
Feb-10
Apr-10
Jun-10
Aug-10
Oct-10
Dec-10
Feb-11
Apr-11
Jun-11
Aug-11
Oct-11
Dec-11
Feb-12
Apr-12
Jun-12
Aug-12
c
Modeled chloride concentrations
Measured chloride concentrations
Cl-concentration (mg/l)
100
90
80
70
60
50
40
30
20
10
0
jan-2009
apr-2009
jul-2009
okt-2009
jan-2010
apr-2010
jul-2010
okt-2010
jan-2011
apr-2011
jul-2011
okt-2011
jan-2012

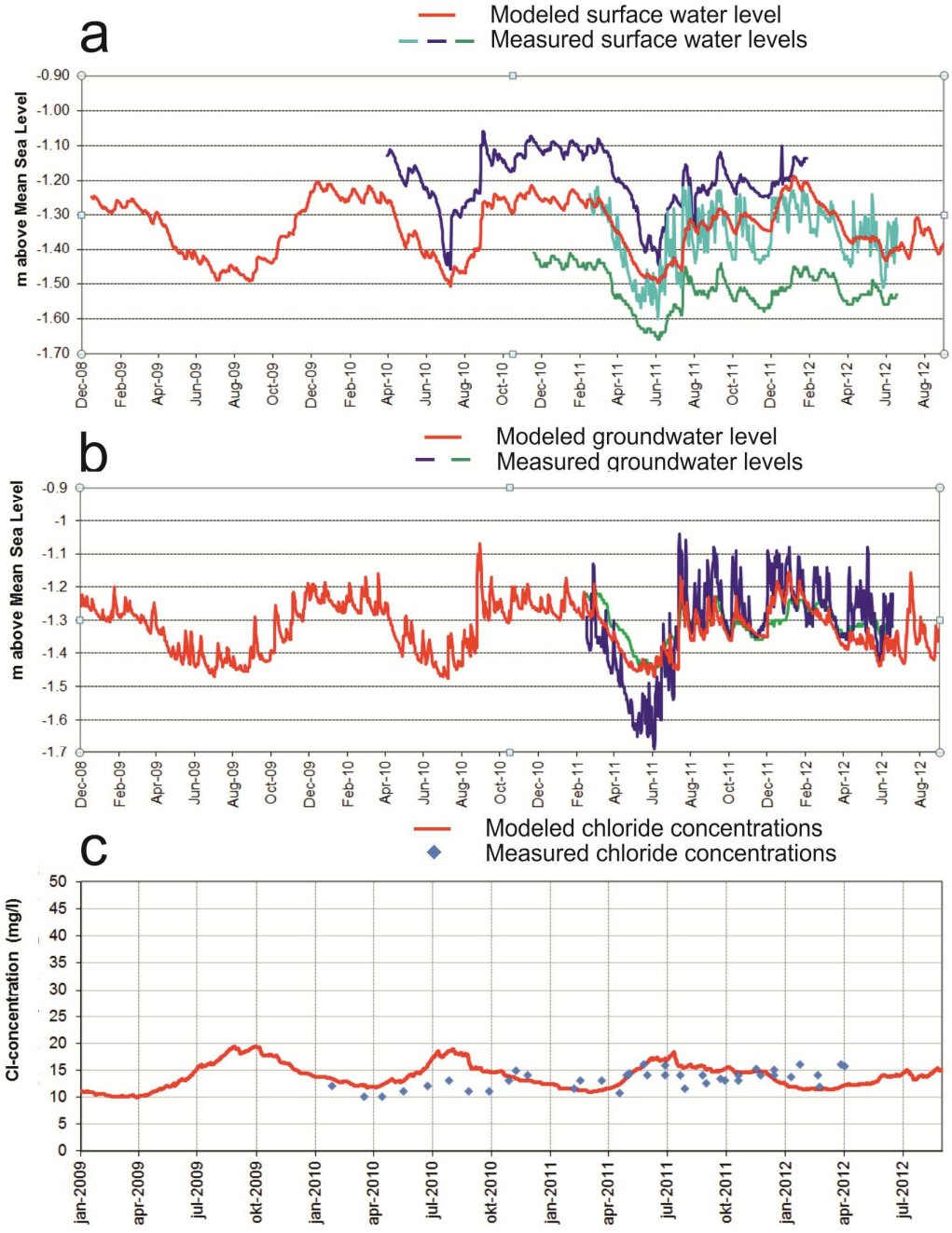
Nieuwe Keverdijkse polder north



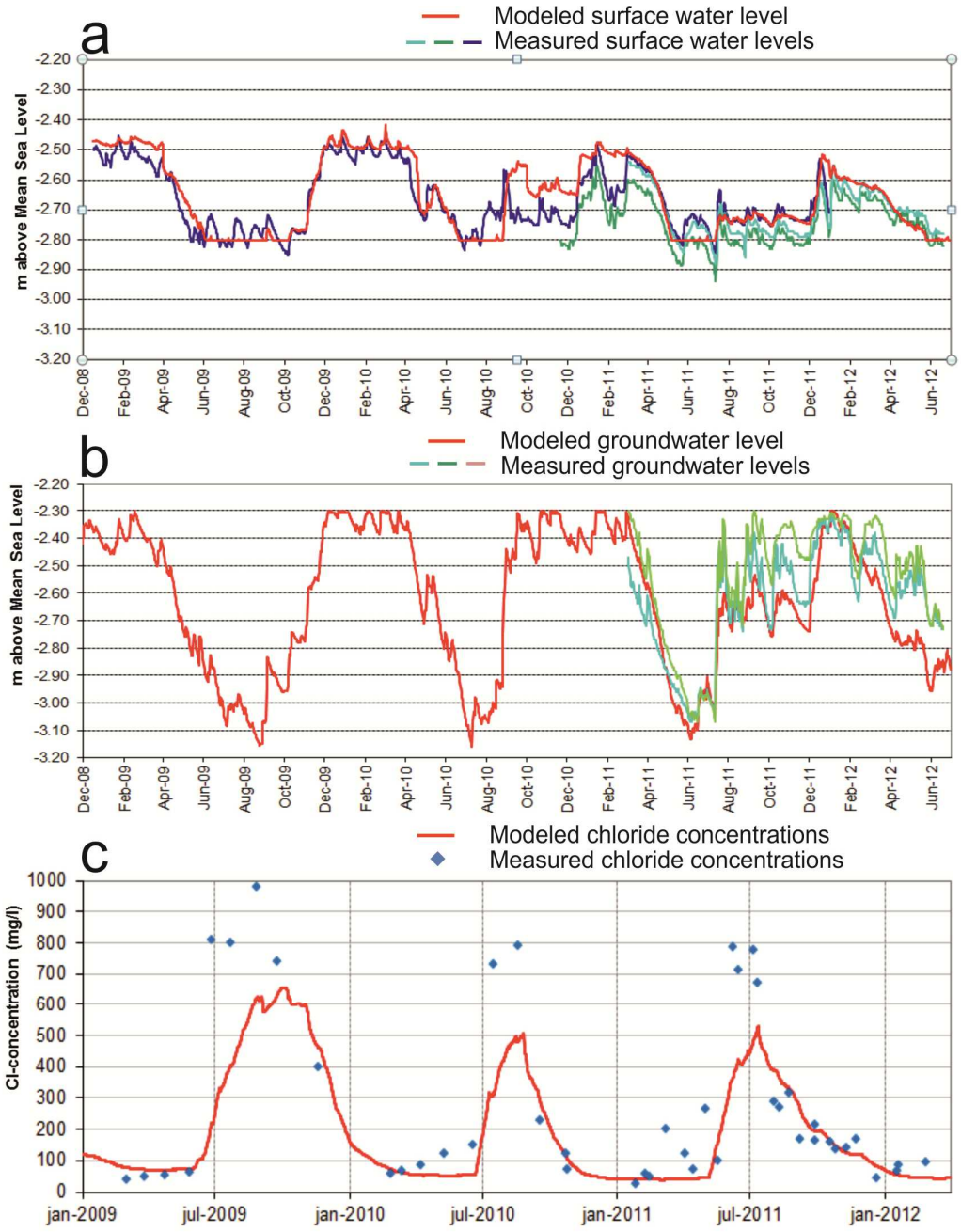
Nieuwe Keverdijkse polder south



Oostelijke Binnenpolder



Ronde Hoep


a
Modeled surface water level
Measured surface water levels
m above Mean Sea Level
-2.20
-2.30
-2.40
-2.50
-2.60
-2.70
-2.80
-2.90
-3.00
-3.10
-3.20
Dec-08
Feb-09
Apr-09
Jun-09
Aug-09
Oct-09
Dec-09
Feb-10
Apr-10
Jun-10
Aug-10
Oct-10
Dec-10
Feb-11
Apr-11
Jun-11
Aug-11
Oct-11
Dec-11
Feb-12
Apr-12
Jun-12
b
Modeled groundwater level
Measured groundwater levels
m above Mean Sea Level
c
Modeled chloride concentrations
Measured chloride concentrations
Cl-concentration (mg/l)
1000
900
800
700
600
500
400
300
200
100
0
jan-2009
jul-2009
jan-2010
jul-2010
jan-2011
jul-2011
jan-2012

Westbroekse Zodden