Summary

Coastal zones are among the world's most densely populated and economically important areas, putting pressure on generally limited available freshwater resources. Global change will undoubtedly increase this pressure, through the combined effects of population increase, economic development, sea level rise, rising evapotranspiration, over-extraction and salinization of coastal aquifers, decreasing river discharges and accelerating land subsidence. In coastal low elevation areas, saline groundwater may flow upward and exfiltrate to surface water, rendering it unfit for freshwater-dependent agriculture, drinking water production, industrial use and vital aquatic ecosystems. Saline groundwater exfiltration is a common issue in the coastal zone of the Netherlands. The hydrological processes and physiographic factors that control saline groundwater exfiltration are, however, not fully understood, hampering successful mitigation strategies. The research presented in this thesis therefore aims to identify the processes and physiographic factors controlling the spatial variability and temporal dynamics of the exfiltration of saline groundwater to surface water and hence the contribution of saline groundwater to surface water salinity.

Given long groundwater travel times, the present-day distribution of groundwater salinity in the coastal zone of the Netherlands still reflects paleo-geographic changes that have occurred during the past millennia. Improved understanding of the effect of paleo-geographic changes on the evolution of groundwater salinity is therefore instrumental to a better understanding of, and simulating future changes to, the present-day groundwater salinity distribution. *Chapter 2* shows results from a paleo-hydrogeological model, simulating the Holocene evolution of groundwater salinity as a result of occurring paleo-geographic changes. Results underlined the long memory of coastal groundwater systems, as, throughout the 8.5 ky model period, the system never reached steady state conditions. Results further indicated a more prominent role of pre-Holocene salt in the present-day groundwater salinity distribution than previously thought.

Surface water salinity dynamics in densely-drained lowland catchments result from saline groundwater exfiltration to tile drains and agricultural ditches, and intake of diverted fresh river water during the growing season to supplement precipitation deficits and dilute salinity levels. A field-scale measurement set-up to separate the different summer flow paths of water and salinity, located in the Schermer polder, is presented in *Chapter 3*. Measurement results showed a non-linear response of tile drain discharge during precipitation events; tile drain salinity was lowest, but transported the majority of groundwater-derived salt to surface water. Drainage to the ditch responded linearly to precipitation, ditch drainage dominated low flow periods. Dynamics in the observed salinity of exfiltrating drain and ditch water could be explained from the interaction between the fast-responding pressure distribution in the subsurface, which determined groundwater flow paths, and the slow-responding groundwater salinity distribution. The water demand for controlling salinity (through flushing) and maintaining water levels to enable sprinkling irrigation was found to greatly exceed concurrent sprinkling irrigation water demand.

Hydrograph separation using environmental tracers is difficult in heavily impacted agricultural catchments, especially when catchment discharge consists of a large number of distinct sources of water. *Chapter 4* outlines G-EMMA, a methodology that, by accounting for uncertainty, extends the use of end-member mixing models to such catchments. Hydrograph separation in an agricultural catchment in polder Haarlemmermeer using G-EMMA enabled an integrated view of the time-varying processes operating in the investigated catchment. Results showed fresh, shallow groundwater to dominate discharge peaks, while saline regional groundwater flow, exfiltrating predominantly by means of boils, provided a constant input of salt in the catchment. Diverted fresh river water amounted to about 50% of total catchment discharge during the agricultural growing season.

Using different observational data types is commonly regarded good practice to constrain model parameter estimates, but their value may be obscured by errors in the model structure or in the observations. *Chapter 5* investigates the value of observations of heads, flow, solute concentration and temperature to constrain a detailed, variable-density groundwater flow and transport model of the Schermer field site (chapter 3). Results showed that, while the value of different conditioning data was less evident than in previously-reported idealized synthetic experiments, the combination of different observational data types was essential to constrain the uncertainty in simulated heads and flow, as well as in simulated groundwater exfiltration salinity. The calibrated model elucidated the processing governing the salinity dynamics in exfiltrating drain and ditch water. The model showed that these dynamics result from the interaction between the fast-responding groundwater flow paths, and the slow-responding groundwater salinity distribution. Additionally, the preferential exfiltration of previously-infiltrated surface water keeps ditch exfiltration salinities low for extended periods after the groundwater system reverts to a draining state.

Chapter 6 presents a rapid, well-identifiable model to simulate salinity dynamics of exfiltrating groundwater, to support operational water management of freshwater resources in coastal lowlands. The Rapid Saline Groundwater Exfiltration Model (RSGEM) simulates groundwater exfiltration salinity dynamics as driven by the interplay between the gradually adjusting subsurface salinity distribution, and the fast flow path response to groundwater level changes. Applied to the Schermer field site, the model showed good correspondence to measured groundwater levels, exfiltration rates and salinity response. Moreover, RSGEM results were very similar to the detailed, complex groundwater flow and transport model of chapter 5. While model results are promising, further work is needed to evaluate model performance in different physiographic settings.

This thesis shows the salinity of groundwater exfiltrating in polders in the Netherlands and hence surface water salinity to vary on a wide range of spatial and temporal scales. Salinity of groundwater exfiltration is highly dynamic, driven by the interaction between the fast-responding groundwater flow paths, and the slow-responding groundwater salinity distribution. Strong heterogeneity in groundwater exfiltration salinity and confinement of extraneous inlet water to preferential flow routes cause significant spatial variation in surface water salinity on the catchment scale. Spatial variation on larger spatial scales still reflects paleo-geographical changes occurring over millennial time scales.