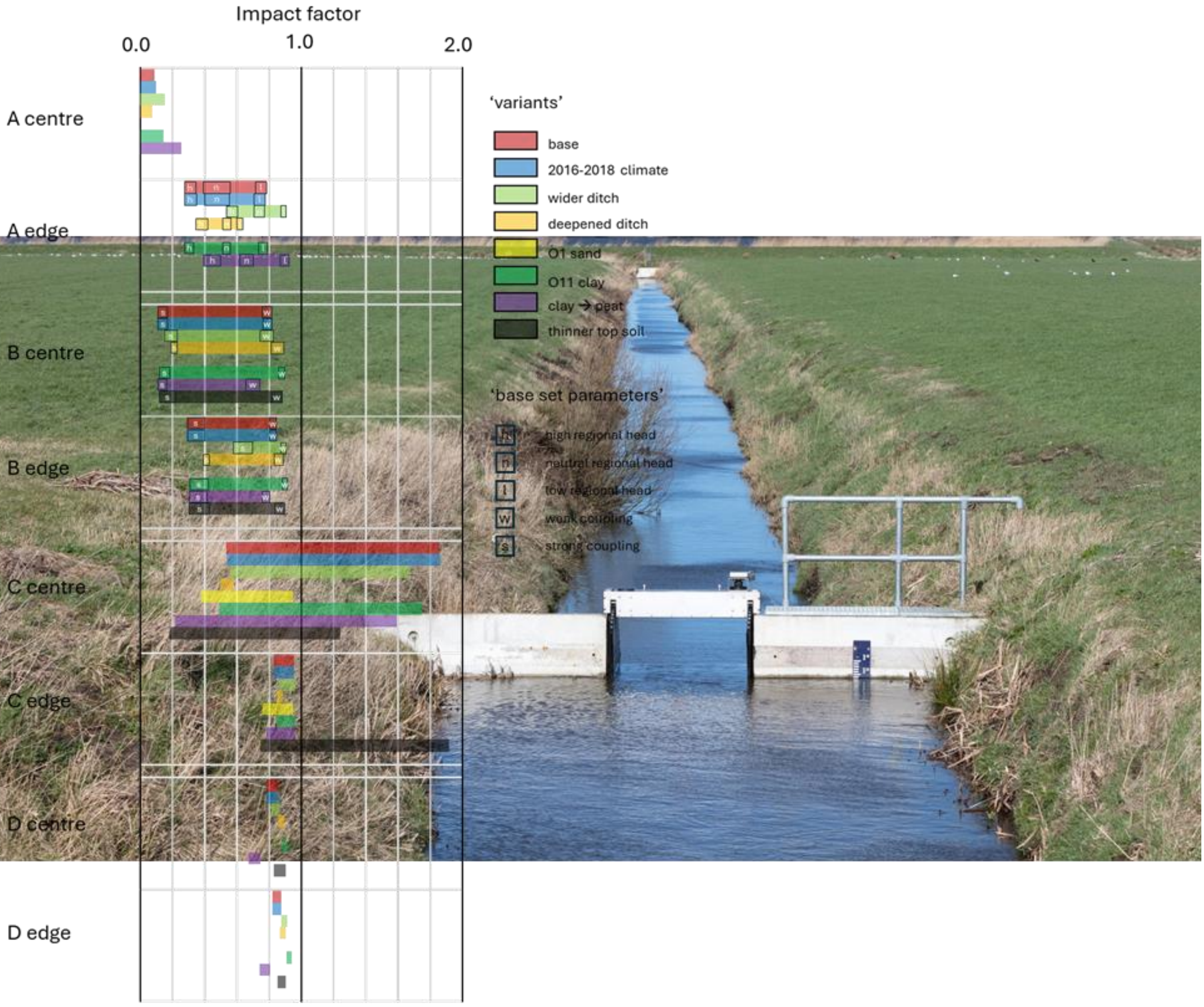
Deltares

Groundwater table lowering due to surface water lowering

Knowledge-base for damage-risk assessment (KEM-16b)



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Summary

Background and project goal

In The Netherlands, differential settlement is a common source of damage to real estate on shallow foundations or wooden pile foundations (houses, sheds, barns, fences). The settlement can have many causes. Changes in groundwater conditions are often at the heart of the problem. Especially groundwater table (GWT) lowering poses a risk since it can cause or enhance (differential) settlement through the shrinkage or compression of soft soil (settlement), oxidation of peat, and degradation of wooden (pile) foundations. The causes of GWT lowering can also be manifold, including groundwater extraction, groundwater drainage by leaky sewers, periods of drought, and lowered surface water levels.

Mining-induced land subsidence can contribute to the above damages through the lowering of surface water levels (SWL) relative to the land surface, both gradually, without interference, and by active lowering. Assessment of the associated damage risk is challenging as it involves a link chain with multiple links. This report concerns the link between SWL lowering and GWT lowering and addresses the question: *How much lowering of the GWT is caused by a given lowering of the SWL?* The GWT shows natural variations through the year. The focus is on the lowering of the annually lowest GWT that is relevant for damage risk.

Present guidance on the GWT impact of SWL lowering is provided by but two existing studies [3,4]. Although valuable, the guidance is considered incomplete and outdated for general use in risk assessment. This report presents a comprehensive groundwater modelling effort to extend the knowledge base of the chain link between SWL lowering and GWT lowering and to provide an improved practical framework for the assessment of the GWT lowering that is caused by SWL lowering. This report builds on foundational work laid down in an interim report [1].

The employed classification of hydrogeological conditions, presented in [1], is based on (a) the connectivity of the water courses and the local groundwater system, (b) storage properties of soil layers and (c) interaction of the local with the regional groundwater system via the underlying aquifer. The classification comprises of four archetypal vertical soil profiles (A-D) that are combined with six classes for regional groundwater system influence, yielding a total of 24 classes. For each of these classes, which are all found in polder-type settings, the GWT conditions were modelled for the very dry climatic conditions of 2018 and for a reference SWL and two lower SWL's (0.2 m lower and 0.5 m lower). The impact of SWL lowering is expressed by an impact factor, calculated as the ratio of the GWT lowering to SWL lowering, where GWT is the lowest day-averaged GWT in the year.

The results obtained for the interim report [1] were considered of insufficient quality and, therefore, provisional/preliminary. Various improvements were deemed necessary. These improvements are presented in this report.

Tasks addressed in this report

The work carried out for the present report involved the following tasks:

Preparatory tasks:
P1 Conduct checks on proper calculation of interim results.

P2 Obtain expert opinions inside and outside Deltares on the general approach.

Model improvement tasks:
M1 Improve unsaturated zone water transfer, and groundwater loss by (actual rather than potential) evapotranspiration.
M2 Improve the phreatic soil water storage representation (specific yield) in the modelling.
M3 Determine sensitivity of impact factors to various conditions.

Validation tasks:
V1 Model existing groundwater level time series (detached from SWL lowering).
V2 Inventory SWL lowering plans with water boards that might be utilized for future validation.

Conclusions

1. Presumed problems with improperly calculated (interim) models have been clarified and resolved (task P1).
    - The water balances of the models of the interim report [1] contained unacceptably large water-balance errors (up to 153.9% for soil profile A). This could be (and was) remedied by tightening the convergence criteria.
    - The unrealistic spiked GWT response to precipitation events in the interim models was found to be a deficiency of MODFLOW6. MODFLOW6 calculates a spurious hydraulic head field (and ambiguous GWT) for the following combination of conditions: (a) the imposed recharge exceeds the vertical (saturated) hydraulic conductivity above the GWT, (b) the soil above the GWT contains a finely discretised stack of model cells. This combination occurs in several of the interim models. The issue was resolved by switching to a MetaSWAP-MODFLOW6 code, where MetaSWAP handles unsaturated zone conditions and water transfer.

2. Feedback and support has been obtained on/for the general approach (task P2).
    - One Deltares expert and two external experts reviewed the interim report [1]. The experts judged the general approach “defensible”, “yields useful insights” and “workable/practicable”. The experts also confirmed the concerns/considerations and needs for improvement that were raised in the interim report [1]:
    - ✓ The need for improved unsaturated zone processes representation.
    - ✓ The unrealistic nature of the peaks in the GWT response to precipitation events.
    - ✓ The need for more extensive sensitivity analysis.
    - Guided by specific comments, the parametrization of the high and low regional head in the models was modified to prevent unrealistic, excessive magnitudes of upward and downward seepage in the model set.

3. The representation and controls of unsaturated zone water transfer and storage are improved in the modelling (tasks M1 and M2).
    - These improvements were achieved though usage of the MetaSWAP-MODFLOW6 code, where MetaSWAP handles the unsaturated zone.
    - To allow use of MetaSWAP for the current project, the coupling with MODFLOW6 was recoded to ensure that MetaSWAP couples with the GWT-containing cell, both in model time steps and in the iterative scheme.

4. A historical GWT time series has been modelled, providing a basic validation of the modelling approach with MetaSWAP-MODFLOW6 and the adopted parametrization systematics (task V1).
    - The modelling reproduces the key characteristics of a GWT-time series in a thick clayey profile in the north of the province of Groningen (near Termunten).

5. A comprehensive dataset of impact factors has been generated. Besides the base model set – this corresponds to the model set developed in the interim report – variants thereof were used to quantify the sensitivity of the impact factors to various parameters and conditions (task M3). This dataset of impact factors, the underlying GWT time series, and the understanding thereof, represents the (improved) knowledge base of the chain link between SWL lowering and GWT lowering.

6. A graphical table (Figure 7-6) has been developed as a practical entry for estimating the impact factor (range) for a specific area or the site location of an individual building.
    - The table provides impact factor ranges for the four soil profile types (A,B,C and D), a location a few meters from a parcel-bounding ditch (at the ‘edge’), and for locations substantially further from the ditches (at the parcel ‘centre’). For some of these ranges, information about the coupling with the regional (ground)water system can be used to reduce the (uncertainty) range.
    - The impact factor for soil profile type C has a very large (uncertainty) range (0.1 – 2.0). The impact factor is not bounded by a maximum value of 1: GWT lowering can exceed SWL lowering. Due to the complex sensitivities, uncertainty reduction requires detailed knowledge of many factors.

7. The 1987 guidelines (Commissie Bodemdaling door Aardgaswinning [3]), which use a classification in terms of a single dominant soil type clay, sand or peat, provide impact factor ranges that are too small: impact factors can both be significantly underestimated and overestimated. Other factors than merely clay, sand or peat exert a strong and often dominant control on the impact factor and, therefore, need to be considered. These factors include the deeper subsoil permeability structure represented by the four soil profile types (A to D) of the present study, and the coupling with the regional (ground)water system.

8. Inventory of SWL adjustment plans with the water boards of The Netherlands has yielded one potential opportunity for a validation study near Marum, Groningen.

Recommendations

The following recommendations are made:

1. It is recommended to develop a series of example problems to clarify the use of the new tool. These examples should clarify what information can be used, and how the information can be used to judge (a) the applicable soil profile type, and (b) the applicable regional (ground)water coupling conditions that are distinguished in the employed classification system. It is recommended to incorporate the example problems a ‘user guide’. The user guide should also clarity the scope/limitations of the new impact factor table.

2. It is recommended to further clarify the potential of the SWL adjustment plans by Waterschap Noorderzijlvest near Marum, Groningen, late 2026, for development of a validation study. And if positive, to carry out the study.

3. It is recommended to conduct field research into the occurrence of conditions that (according to the modelling) can result in impact factors > 1 (soil profile type C). This can be done by studying the mean deepest GWT (GLG) for sites with this type of soil profile, between ditch and the middle of the parcel, using hydromorphic features derived from vertical coring.

Samenvatting

Achtergrond en doel van het project

In Nederland is differentiële zetting een veel voorkomende bron van schade aan gebouwen op ondiepe funderingen of houten paalfunderingen (huizen, schuren, schuren, muren). De zetting kan vele oorzaken hebben, maar verandering van de grondwaterstand (GWS) speelt over het algemeen een grote rol. Met name GWS verlaging is risicovol omdat het kan bijdragen aan zakking door krimp van klei en samendrukking van klei en veen (meestal aangeduid met de term zetting), oxidatie van organisch-rijke afzettingen zoals veen, en aantasting van houten funderingselementen. De mogelijke oorzaken van GWS verlaging zijn ook divers, zoals grondwateronttrekking, grondwater lekkage door riolering, perioden van extreme droogte en verlaagde oppervlaktewaterpeilen.

Mijnbouw gerelateerde bodemdaling zoals door de gaswinning kan aan bovenstaande zettingsschade bijdragen door verlaging van het oppervlaktewaterpeil (OWP) ten opzichte van het maaiveld. Deze OWP verlaging door diepe bodemdaling kan zowel geleidelijk, zonder enig ingrijpen ontstaan, als door actieve peilaanpassingen door de waterschappen. Schaderisicobeoordeling door OWP verlaging is lastig omdat de schadeontwikkeling een keten betreft die bestaat uit meerdere schakels. Dit rapport richt zich op de schakel tussen OWP verlaging en GWS verlaging en adresseert de vraag: *Hoeveel GWS verlaging wordt veroorzaakt door een gegeven OWP verlaging?* De GWS vertoont onder normale omstandigheden variaties door weersinvloeden. De aandacht in deze studie gaat uit naar verlaging van de jaarlijks laagste GWS die het meest relevant is voor schaderisico.

De huidige handvatten voor het schatten van de GWS impact van OWP verlaging bestaan hoofdzakelijk uit twee studies [3,4]. Hoewel van waarde, zijn deze handvatten incompleet en achterhaald, waardoor ze ontoereikend geacht worden voor schaderisicobeoordeling. Dit rapport presenteert een uitgebreide grondwatermodelleerstudie, bedoeld om de kennisbasis van de schakel tussen OWP verlaging en GWS verlaging te vergroten, en om een verbeterd praktisch raamwerk te bieden voor de beoordeling van GWS verlaging als gevolg van OWP verlaging. Dit rapport bouwt voort op funderend werk dat is gepresenteerd in een interim rapport [1].

De opgestelde classificatie van hydrogeologische situaties, gepresenteerd in [1], is gebaseerd op (a) de connectiviteit tussen de lokale watergangen en het lokale grondwatersysteem, (b) de bergingseigenschappen van de bodemlagen en (c) de interactie tussen het lokale en omliggende grondwatersysteem via het onderliggende watervoerende pakket. De classificatie bestaat uit vier archetypen voor de bodemopbouw (A-D) die worden gecombineerd met zes klassen voor de koppeling met het regionale grondwatersysteem, wat resulteert in een totaal van 24 klassen. Voor elk van deze klassen, die allemaal betrekking hebben op een polder omgeving, zijn berekeningen uitgevoerd voor de zeer droge klimatologische omstandigheden van 2018, en voor een referentie OWP en twee lagere OWP’en (0,2 m lager en 0,5 m lager). De impact van de twee OWP verlagingen is gekwantificeerd middels een impact factor, berekend als de verhouding van de GWS verlaging en de OWP verlaging, waarbij voor de GWS de laagste GWS op dagbasis is genomen in het gesimuleerde jaar.

De resultaten van het interim rapport [1] waren nog onvoldoende en daarom voorlopig van aard. Diverse verbeteringen werden nodig geacht. Deze verbeteringen zijn doorgevoerd in het voorliggende rapport.

Werkzaamheden die zijn uitgevoerd in dit rapport

De werkzaamheden die in het kader van dit rapport zijn verricht, omvatten de volgende taken:

Voorbereidende taken:
P1 Uitvoeren van controles op de juistheid van berekening van de tussentijdse resultaten.
P2 Verkrijgen van deskundigen advies van binnen en buiten Deltares over de algemene aanpak.

Taken voor modelverbetering:
M1 Verbetering van de watertransport in de onverzadigde zone en grondwaterverlies door (de werkelijke in plaats van de potentiële) evapotranspiratie.
M2 Verbetering van de bodemwaterberging (‘specific yield’) in de modellering.
M3 Gevoeligheidsanalyse van impactfactoren voor verschillende omstandigheden.

Validatie taken:
V1 Modellering van bestaande tijdreeksen van grondwaterstanden (los van OWP-verlaging).
V2 Inventarisatie OWP-verlagingsplannen van NL-waterschappen die mogelijk kunnen worden benut voor toekomstige validatie.

Conclusies

1. Veronderstelde problemen met onjuist berekende (tussentijdse) modellen zijn opgehelderd en opgelost (taak P1).
    - De waterbalansen van de modellen van het tussentijds rapport [1] bevatten onaanvaardbaar grote waterbalansfouten (tot 153,9% voor bodemprofiel A). Dit kon worden (en werd) verholpen door de convergentiecriteria aan te scherpen.
    - De onrealistische piekende GWT-respons op neerslaggebeurtenissen in de tussentijdse modellen bleek een tekortkoming van MODFLOW6 te zijn. MODFLOW6 berekent een foutief stijghoogteveld (en dubbelzinnige GWT) voor de volgende combinatie van omstandigheden: (a) de opgelegde grondwateraanvulling overschrijdt de verticale (verzadigde) hydraulische conductiviteit boven de GWT, (b) de grond boven de GWT bevat een fijn gediscretiseerde ‘stack’ van modelcellen. Deze combinatie komt voor in verschillende van de interim-modellen. Het probleem is opgelost door over te schakelen naar een MetaSWAP-MODFLOW6-code, waarbij MetaSWAP de omstandigheden in de onverzadigde zone en het watertransport afhandelt.

2. Er is feedback en ondersteuning verkregen op/voor de algemene aanpak (taak P2).
    - Eén Deltares expert en twee externe deskundigen hebben het tussentijds rapport [1] gereviewd. De experts beoordeelden de algemene aanpak als "verdedigbaar”, “levert bruikbare inzichten op" en "werkbaar/uitvoerbaar". De deskundigen bevestigden ook de zorgen/overwegingen en behoeften voor verbetering die in het interim rapport naar voren werden gebracht [1]:
    - ✓ De noodzaak om onverzadigde zone processen beter te modelleren.
    - ✓ De onbetrouwbaarheid van de piekende GWT-respons op neerslaggebeurtenissen.
    - ✓ De behoefte aan een uitgebreidere gevoeligheidsanalyse.
    - Aan de hand van specifieke opmerkingen werd de parametrisering van de hoge en lage regionale stijghoogte in de modellen aangepast om onrealistische, buitensporige kwel en wegzijging in de modellen te voorkomen.

3. De simulatie van watertransport en bodemwaterberging in de onverzadigde zone is verbeterd (taken M1 and M2).
    - Deze verbeteringen werden bereikt door gebruik te maken van de MetaSWAP-MODFLOW6-code, waarbij MetaSWAP de onverzadigde zone afhandelt.
    - Om het gebruik van MetaSWAP voor het huidige project mogelijk te maken, werd de koppeling met MODFLOW6 gehercodeerd om ervoor te zorgen dat MetaSWAP koppelt met de GWT-bevattende cel, zowel in modeltijdstappen als in het iteratieve schema.

4. Er is een historische GWT-tijdreeks gemodelleerd, die een basisvalidatie biedt van de nieuwe modelleringsaanpak met MetaSWAP-MODFLOW6 en van de gebruikte parametrisatiesystematiek (taak V1).
    - De modellering reproduceert de belangrijkste kenmerken van een GWT-tijdreeks in een dik kleirijk profiel in het noorden van de provincie Groningen (bij Termunten).

5. Er is een uitgebreide dataset van impactfactoren gegenereerd. Naast de basismodelset – deze komt overeen met de modelset die in het interim rapport is ontwikkeld – zijn varianten daarvan gebruikt om de gevoeligheid van de impactfactoren voor verschillende parameters en condities te kwantificeren (taak M3). Deze dataset van impactfactoren, de onderliggende GWT-tijdreeksen en het begrip daarvan, vertegenwoordigt de (verbeterde) kennisbasis van de schakel tussen SWL-verlaging en GWT-verlaging.

6. Een grafische tabel (Figure 7-6) is ontwikkeld als praktische ingang voor het schatten van de impactfactor (bandbreedte) voor een specifiek gebied of voor de locatie van een individueel gebouw.
    - De tabel geeft impactfactorbandbreedtes voor de vier grondprofieltypen (A, B, C en D), een locatie op enkele meters van een perceelsgebonden sloot en voor locaties die aanzienlijk verder van de sloten liggen. Voor een aantal van deze bandbreedtes kan informatie over de koppeling met het regionale (grond)watersysteem worden gebruikt om de (onzekerheids)bandbreedte te verkleinen.
    - De impactfactor voor bodemprofiel type C heeft een zeer grote (onzekerheids)marge (0,1 – 2,0). De impactfactor is niet begrensd door een maximale waarde van 1: GWS-verlaging kan OWP-verlaging overschrijden. Vanwege de complexe gevoeligheden vereist onzekerheidsreductie gedetailleerde kennis van veel factoren.

7. De handvatten/richtlijnen uit 1987 (Commissie Bodemdaling door Aardgaswinning [3]), die zijn gebaseerd op een enkelvoudige dominante grondsoort (klei, zand of veen), geven te kleine impactfactorbandbreedtes. Dat wil zeggen, met deze oude richtlijnen kunnen impactfactoren zowel aanzienlijk worden onderschat als overschat. Andere factoren dan alleen klei, zand of veen oefenen een sterke en vaak dominante invloed uit op de impactfactor. Deze factoren zijn onder meer de diepere doorlatendheidsstructuur van de ondergrond van de vier bodemprofieltypen (A t/m D) van dit onderzoek, en de koppeling met het regionale (grond)watersysteem.

8. Inventarisatie van OWP-aanpassingsplannen van de waterschappen in Nederland heeft één plan (omgeving Marum, Groningen) opgeleverd die kansen biedt voor een validatiestudie.

Aanbevelingen

De volgende aanbevelingen worden gedaan:

1. Het wordt aanbevolen om een reeks voorbeeldproblemen uit te werken om het gebruik van de nieuwe tool te verduidelijken. Deze voorbeelden moeten duidelijk maken welke

informatie kan worden gebruikt, en hoe de informatie kan worden gebruikt om een goede inschatting te maken van (a) het toepasselijke bodemprofieltype, en (b) de toepasselijke regionale (grond)waterkoppelingscondities die in het gehanteerde classificatiesysteem worden onderscheiden. Het is aan te raden om de voorbeeldproblemen op te nemen in een 'gebruikershandleiding'. De gebruikershandleiding moet ook duidelijkheid verschaffen over de reikwijdte/beperkingen van de nieuwe impactfactortabel.

2. Aanbevolen wordt om de voorgenomen OWP-aanpassingsplannen van Waterschap Noorderzijlvest bij Marum, Groningen, eind 2026, verder te onderzoeken als mogelijkheid voor de ontwikkeling van een validatiestudie. En indien positief, om het onderzoek uit te voeren.

3. Het wordt aanbevolen om veldonderzoek te doen naar het vóórkomen van omstandigheden die (volgens de modellering) kunnen resulteren in impactfactoren > 1 (bodemprofieltype C). Dit kan worden gedaan door voor locaties met dit type bodemprofiel, tussen sloot en het midden van het perceel, de gemiddelde diepste GWS (GLG) te bestuderen met behulp van hydromorfe kenmerken die worden afgeleid uit verticale boringen.

Contents

1 Introduction

The work reported here was carried out in the framework of the *Knowledge Program on Effects of Mining* (KEM-16b *Relation between subsidence and damage*), funded by the Ministry of Economic Affairs (EZK)[1]. The work represents a continuation of work started in 2022 in KEM16 *Toolbox subsidence*. The preliminary results of this prior work were reported in [1].

1.1 Background

1.1.1 Issue

In The Netherlands, differential settlement is a common source of damage to real estate on shallow foundations or wooden pile foundations (houses, sheds, barns, fences). The settlement can have many causes. Changes in groundwater conditions are often at the heart of the problem. Especially groundwater table (GWT) lowering poses a risk since it can cause or enhance (differential) settlement through the shrinkage or compression of soft soil (settlement), oxidation of peat, and degradation of wooden (pile) foundations. The causes of GWT lowering can also be manifold, including groundwater extraction, groundwater drainage by leaky sewers, periods of drought, and lowered surface water levels.

Mining-induced land subsidence can contribute to the above damages through the lowering of surface water levels (SWL) relative to the land surface, both gradually, without interference, and by active lowering[2]. Assessment of the associated damage risk is challenging as it involves many factors.
Figure 1-1 depicts the link chain between SWL lowering and building damage. The focus of the present report is on the link between components 1 and 2 of the link chain: *How much lowering of the groundwater table occurs for a given lowering of the surface water level?*

For a constant SWL, the GWT is not constant; it fluctuates in response to weather conditions (precipitation and evapotranspiration) and sometimes temporal variations in groundwater pumping or recharge from leaky sewers. The range of fluctuation is typically about half a metre but can vary from about one decimetre to several meters. Also, in many polder areas in The Netherlands the fluctuating GWT can be affected by seasonally varying SWL because the target SWL in the growing season is often set somewhat higher than in the target SWL in the winter season. The full characteristics of the GWT fluctuations are not of concern in this report. Neither are the impacts of temporary SWL drops. As *low* GWTs are most relevant to differential settlement and associated damage risk, the focus of this study is the impact of permanent or very long-lived SWL lowering on “damage-determining” *low* GWTs.

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[1] More recently the Ministry of Climate policy and Green Growth (KGG).

[2] Appendix A elucidates the two ways in which water level lowering can develop in response to mining-induced subsidence. The water level lowering relative to the land surface is of concern here rather than absolute water level lowering (relative to the Dutch ordnance level NAP) because mining-induced subsidence tends to lower both the land surface and the water level. In water management, the difference between land level and the water level in the waterways is referred to as *freeboard*. The relevant surface water level lowering therefore can in more general terms be referred to as freeboard increase.

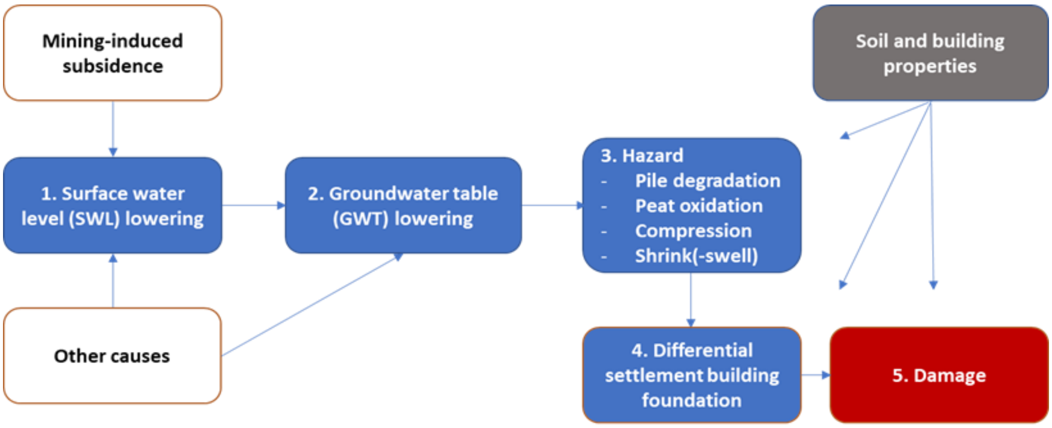


Figure 1-1 Graphic depicting the link chain between surface water level lowering (component 1) and building damage (component 5). The chain links (arrows) that link the components, require quantification in damage risk assessment. The focus of the present report is on the link between components 1 and 2. Source: [2].

The current knowledge base of the chain link between SWL lowering and GWT lowering is incomplete and outdated, and largely inadequate for general use. Two key studies that comprise the knowledge base were presented and discussed in the previous report [1]. The first of these studies, commissioned by the Commissie Bodemdaling door Aardgaswinning [3], involving groundwater modelling, dates back more than 35 years to a time when modelling capabilities were still rather limited. Moreover, key aspects of the underlying modelling are unknown. The adopted classification in terms of three ‘soil classes’ represented by a single lithology is expected to overlook the role of other geohydrological factors such as shallow aquifers, their connectivity with the water courses and upward or downward seepage conditions. The second study [4] concerned monitoring of GWL lowering adjacent to a drainage outlet canal (Dutch: boezemkanaal) upon SWL lowering. Albeit informative, the broader significance of the results is unclear, and part of the monitoring data and results were considered unreliable.

1.1.2 Overall objective

The objective of the work started in 2022 (KEM16) is to extend the knowledge base of the chain link between SWL lowering and GWT lowering. The aim of the work is to generate knowledge/information for establishing a practical set of tables that can be used in the context building damage (risk) assessment.

1.1.3 Approach

A modelling approach is used to develop the knowledge base and to establish the practical tool. Modelling provides the only means to develop the required generic framework. Usable observational datasets of the GWT response to SWL lowering are largely non-existent. The modelling is conducted for a polder-type setting characterized by fairly regular spaced water courses such as ditches, separating parcels of land. This general setting occurs over large areas in the coastal provinces of The Netherlands. In these areas, Holocene strata generally overly an extensive Pleistocene aquifer system. The Holocene cover commonly includes relatively low-permeability soft soil units (clay, peat), but can also be intercalated with permeable sand layers.
Key factors that are expected to influence the response of seasonally low GWT’s to SWL lowering in these settings are:

- Connectivity of the water courses and groundwater system (in the parcels).
- Storage properties of the soil layer(s) in which the GWT declines during drought.

- Coupling of the GWT and the SWL of the parcel-bounding water courses with the regional groundwater system via an underlying extensive aquifer.

Based on these factors, distinctive classes of hydrogeological conditions are defined (in [1] 24 classes were used, these classes are reiterated in chapter 2 of this report). For each of these classes the GWT is modelled for dry climatic conditions. This is done for a reference SWL in the parcel-bounding water courses and for lowered SWLs. The impact of SWL lowering on the GWT is expressed by an impact factor, calculated as the ratio of the GWT lowering to SWL lowering. Results are meant to provide a basis to discern classes that can be associated with distinctive impact factors that may be turned into tables for practical use in damage risk assessment.

1.1.4 Interim results (2022/2023)

Impact factors were derived in [1] for 24 classes of hydrogeological conditions. The preliminary results showed dependency of the impact factors on (i) soil stratification, both in the depth range of the parcel-bounding water courses as well as at deeper levels, and (ii) the way in which large regional water bodies (canals, lakes) are coupled with the underlying aquifer. A special finding was that impact factors for certain classes (significantly) exceed 1, indicating that the GWT can lower more than the SWL lowering.

The results were considered of insufficient quality and, therefore, provisional/preliminary. Various improvements were deemed necessary. These improvements are made in this report.

1.2 Objective and tasks of this report

The goal of the work presented in this report is to advance the work carried out thus far (described in paragraph 1.1 and [1]) and to generate results that can be used for establishing a practical set of tables that can be used in the context building damage (risk) assessment.

To reach this goal the following tasks were set:

Preparatory tasks:
P1 Conduct checks on proper calculation of interim results.
P2 Obtain expert opinions inside and outside Deltares on the general approach.

Model improvement tasks:
M1 Improve unsaturated zone water transfer, and groundwater loss by (actual rather than potential) evapotranspiration.
M2 Improve the phreatic soil water storage representation (specific yield) in the modelling.
M3 Determine sensitivity of impact factors to various conditions.

Validation tasks:
V1 Model existing groundwater level time series (detached from SWL lowering).
V2 Inventory SWL lowering plans with water boards that might be utilized for future validation.

1.3 Reading guide

The remainder of this report is structured as follows:

Chapter 2 reiterates the classification scheme that was established in the first report. This scheme provides the framework that is used to explore different settings that are anticipated to be associated with different groundwater responses to SWL lowering.

Chapter 3 reports the outcomes of the preparatory tasks P1 and P2, and the implications therefrom for the general approach and tasks of the present study.

Chapter 4 presents the model improvement tasks M1 and M2. The results of validation task V1 are included in this chapter to illustrate the appropriateness of the administered improvements.

Chapter 5 subsequently provides an overview of the model variants that were defined to study SWL-lowering impact factors. The full set includes both the base set that was used in the previous report, and the additional variants that comprise the sensitivity analysis of task M3.

Chapter 6 presents the results of the calculated model set. The impact factors are presented in numerical tables. More comprehensive illustrations of model results (e.g., time series of the GWT and momentary GWT cross-sections across the parcel) are provided for selected models.

Chapter 7 analyses and discusses the results. The characteristics and sensitivity of the impact factors and their key controls are elucidated and visualized. A new practical table is presented and compared with the 1987 guidelines of the Commissie Bodemdaling door Aardgaswinning [3].

Chapter 8 reports the outcome of the inventory of SWL lowering plans (task V2).

Chapter 9 closes with conclusions of the present work and recommendations.

Appendix A elucidates how mining-induced land subsidence can cause freeboard increase (SWL lowering relative to the land surface).

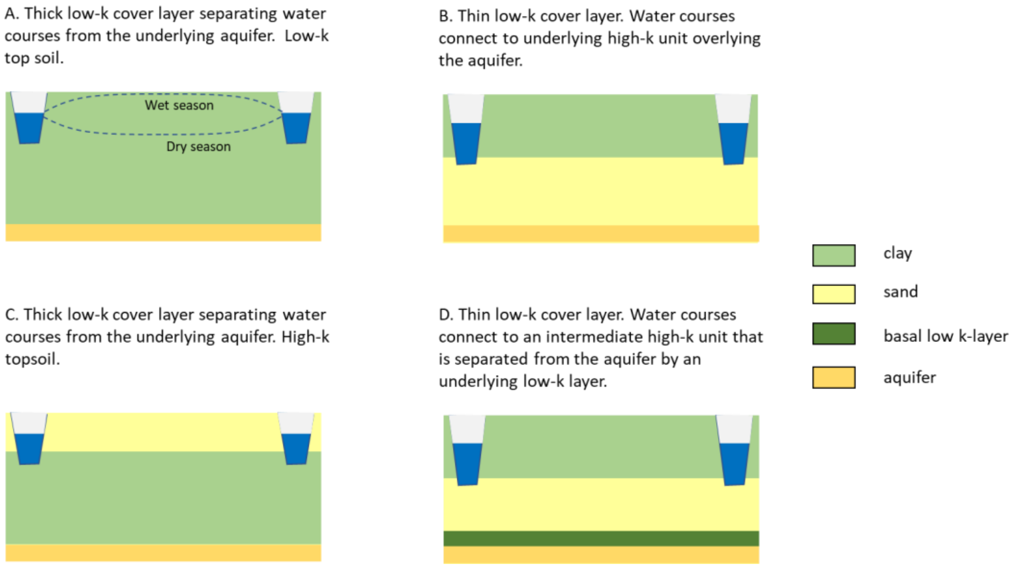
Appendices B to D document the key output of all individual model runs/variants.

2 Reiteration of the classification scheme

To enhance accessibility/legibility of this report, this chapter reiterates the hydrogeological classification described in the interim report [1]. The classification comprises 24 classes. The classes combine four archetypal soil profiles and six ways in which the local, deep aquifer is coupled with a ‘regional SWL or hydraulic head’.

Polder-type setting
The classification is restricted to the polder-type setting characterized by fairly regular spaced water courses such as ditches, separating parcels of land[3]. This general setting occurs over large areas in the coastal provinces of The Netherlands. In these areas, Holocene strata generally overly an extensive Pleistocene aquifer system. The Holocene cover commonly includes relatively low-permeability soft soil units (clay, peat) that exert a dominant influence on the groundwater behaviour. The classification is not necessarily exhaustive for polder areas. For instance, the setup does not address the GWT response adjacent to large water bodies such as drainage outlet canals or lakes.

<u>Four archetypal soil profiles</u>. Figure 2-1 depicts the soil profiles, labelled A to D. Geohydrologists are expected to be able to distinguish these archetypes using online datasets and/or locally acquired borings and/or geotechnical soundings together with information or judgement of the depth of the water courses. Type C, for instance, is common in urban areas where the ‘topsoil’ consists of an anthropogenic cover layer that is applied to improve building and drainage conditions. Types B and D are common in the province of Zuid-Holland where the intermediate sandy layer represents widespread occurrence of tidal deposits (Dutch: wadzand), and the basal low-k layer represents the variable, but widespread occurrence of basal peat (Dutch: basisveen).


A. Thick low-k cover layer separating water courses from the underlying aquifer. Low-k top soil.

B. Thin low-k cover layer. Water courses connect to underlying high-k unit overlying the aquifer.

C. Thick low-k cover layer separating water courses from the underlying aquifer. High-k topsoil.

D. Thin low-k cover layer. Water courses connect to an intermediate high-k unit that is separated from the aquifer by an underlying low-k layer.

Figure 2-1: Four archetypal soil profiles (vertical cross sections) that were chosen to study the GWT response to SLW lowering in the water courses (blue). ‘Low-k’ and ‘high-k’ refers to permeability. Differences in permeability of the layers are more important for the classification than the specific lithologies (this is discussed in the main text).

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[3] Such a setting is also implied in the modelling presented in [3] (CBA, 1987)

The hydraulic properties are of greater importance in the classification than the specific lithologies (sand, clay) shown in the legend of Figure 2-1. Ripened clays in topsoil's (up to ~ 1.5 m depth), for instance, can be highly permeable due to shrinkage cracks, burrowing and tillage, allowing effective water exchange with parcel-bounding water courses. Despite the topsoil being clay, such a profile may better fit type C than type A. Furthermore, the permeability of peat – peat is not explicitly shown in Figure 2-1 - can be similar to the permeability of fine sand. A profile with a thin clay cover on top of permeable peat, might then fit type B or type D.

Rationale
The rationale for the four soil profiles stems from the different ways in which the parcel bounding water courses (nominally ditches) connect to and interact with the groundwater system.
For type A, the influence of the SWL of the ditches extends a short distance into the parcel. For types B and D, the SWL can influence the hydraulic head in the 'sand' underneath the cover layer and, thereby, the GWT to greater distance from the ditches. However, if this effect prevails also depends on other factors. For type B, the hydraulic head in the sand may be dominated by the extensive aquifer via regional influences (see regional coupling below). For type D, the sand is shielded from the extensive aquifer by the 'basal low k-layer', which makes the ditch-SWL a prominent and robust influence. For type C, the ditches may not only efficiently drain the permeable top soil during wet periods, but also recharge the groundwater in the top soil during dry periods. The efficiency of the latter can be (strongly) reduced by SWL lowering, which may exacerbate the impact of SWL lowering during drought.

<u>Six types of coupling with regional (ground)water system</u>. Table 2-1 summarizes the six types of coupling that are used in the classification. The classes combine three conditions of regional hydraulic head and two conditions for the strength of the coupling with the regional hydraulic head.

High and low regional head conditions are schematically shown in Figure 2-2. A high head stimulates upward seepage at the parcel of interest and a low head stimulates downward seepage. These seepage conditions are expected to play a role in the GWT response to SWL lowering. However, imposing a fixed aquifer head, as is commonly done in parcel-scale groundwater models, is oversimplified and unrealistic. After all, the temporally varying GWT in the polder area (and/or the stable polder SWL) also influences the local aquifer head to a greater or lesser extent[4]. This is indicated by the vertical arrows in Figure 2-2. The relative influence of the regional SWL can, therefore, range from small (weak coupling) to large (strong coupling) depending, amongst others, on the distance of the parcel to regional surface water bodies.

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[4] For instance, when upward seepage is induced by a low GWT during drought, groundwater is taken from the aquifer. If not replenished fully by inflow from surface water, the hydraulic head declines, suppressing upward seepage.

Table 2-1 Six classes of ‘regional influence’ on the aquifer head used in the classification. The regional head can be higher than, the same as (neutral) or lower than the local SWL at the parcel of interest. These external heads can be strongly or weakly coupled to the aquifer at the parcel of interest.

‘regional’ head **coupling**	**high**	**neutral**	**low**
strong	Within the surroundings of the parcel, SWLs (and/or GWT’s) occur that are higher than at the parcel and cause upward seepage at the parcel. One or more waterbodies with high SWL are large and/or nearby and exert a strong influence on the head at the parcel.	Within the surroundings of the parcel, SWLs (and/or GWT’s) are the same as at the parcel and, therefore, do not cause upward or downward seepage at the parcel. One or more waterbodies are large and/or nearby and exert a strong influence on the head at the parcel.	Within the surroundings of the parcel, SWLs (and/or GWT’s) occur that are lower than at the parcel and cause downward seepage at the parcel. One or more waterbodies with low SWL are large and/or nearby and exert a strong influence on the head at the parcel.
weak	Within the surroundings of the parcel, SWLs (and/or GWT’s) occur that are higher than at the parcel and cause upward seepage at the parcel. The waterbodies with high SWL are small, shallow and/or distant and exert a weak influence on the head at the parcel.	Within the surroundings of the parcel, SWLs (and/or GWT’s) are the same as at the parcel and, therefore, do not cause upward or downward seepage at the parcel. The waterbodies are small, shallow and/or distant and exert a weak influence on the head at the parcel.	Within the surroundings of the parcel, SWLs (and/or GWT’s) occur that are lower than at the parcel and cause downward seepage at the parcel. The waterbodies with low SWL are small, shallow and/or distant and exert a weak influence on the head at the parcel.

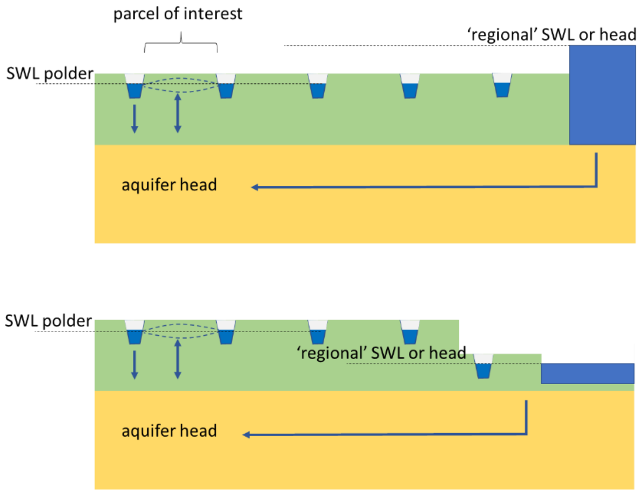

Figure 2-2: Schematic illustration of the way in which regional controls on aquifer head interact with the GWT (and the SWL) at a parcel of interest. Blue arrows do not represent flow, but influence. Top: High heads/SWLs outside the polder affect the local aquifer head at the parcel of interest. When significant, this tends to cause upward seepage which can influence the GWT. The vertical arrows indicate that, conversely, the GWT or a lowering of the SWL may also affect the local aquifer head. Bottom: Low heads/SWLs outside the polder affect the local aquifer head at the parcel of interest. When significant, this tends to cause downward seepage which can influence the GWT. The vertical arrows indicate that, conversely, the GWT or a lowering of the SWL may also affect the local aquifer head.

3 Preparatory tasks

3.1 Checks on interim results

3.1.1 Issues

In the interim report [1], two aspects of the results were flagged to be counterintuitive, signalling potential error in the model calculations, and warranting closer scrutiny.

Issue 1: The GWT time series of soil profile type C displayed a conspicuous spiked response (marked instantaneous rise and fall) to precipitation during the dry spell in which the GWT jumps to the base of the ‘sand cover’ that overlies thick clay. Although a rapid rise is expected, the magnitude of the rise should scale with the (net) precipitation, which varies for the precipitation events in the employed input. Moreover, the subsequent decline should follow a gradual drainage trend rather than being virtually instantaneous. Spiked behaviour was also observed in the time series of soil profile A.

Issue 2: For soil profile A in combination with weak regional coupling, both the high and low regional head classes yielded higher impact factors than the neutral head class. Intuitive system understanding suggests that the magnitude of the impact factor should change monotonously from high, through neutral, to low regional hydraulic head.

3.1.2 Checks and findings

Checks of the water balances of the calculated models revealed that water-balance errors in the calculations often proved unacceptably high (up to 153.9% for soil profile A). This was readily remedied by tightening the convergence criteria. With this adjustment, all models were rerun. This resolved issue 2. However, the adjustment did not resolve issue 1.

Subsequently, individual parameters were varied for models that showed the spiked response to precipitation events with the aim to detect the aspect(s) of the models that elicit(s) the spurious behaviour. It was found the behaviour is closely coupled to the low vertical hydraulic conductivity (of clay). Scrutiny of the model vertical head field at cell stacks during individual time steps, showed that when recharge exceeds the vertical hydraulic conductivity, the MODFLOW6 code yields a solution which conceptually approximates a stack of perched aquifers (Figure 3-1). Apart from the peculiar and unphysical nature of the solution[5,6], the GWT for the solution is ambiguous. In the project, the GWT was/is inferred from the head field by postprocessing as the first head value in the stack (moving down from the land surface), higher than the cell base. For the MODFLOW6 solution, the GWT then corresponds to the head of the ‘topmost perched aquifer cell’. This not only explains the spiked GWT response that was obtained in the interim results (issue 1), but also confirms the unphysical nature of these results.
One of the main reasons this issue was encountered in this study is the unconventional, very fine discretisation (0.05 m cell height) adopted in the top part of the model domain. This choice was made to achieve desired detail in resolving head fields and flow, notably close to the water courses. In coarsely discretised models that are typically used in more conventional modelling of large spatial domains, this is less of an issue. Moreover, in these coarser models

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[5] The solution is unphysical because infiltration cannot exceed the infiltration capacity K_v.

[6] The origin of this solution is unclear, but may have to do with the fact that MODFLOW6 does not cap the vertical hydraulic gradient to a value of 1 for gravity drainage, which would cap vertical (saturated) percolation at K_v, and with the way vertical conductance between grid cells is calculated to quantify the flows for cells with partial saturation (chapter 4 MODFLOW6 manual).

the cell drying/rewetting method may be used to avoid the inferred problem. However, the latter option is not practicable for finely discretized models due to numerical instability issues.

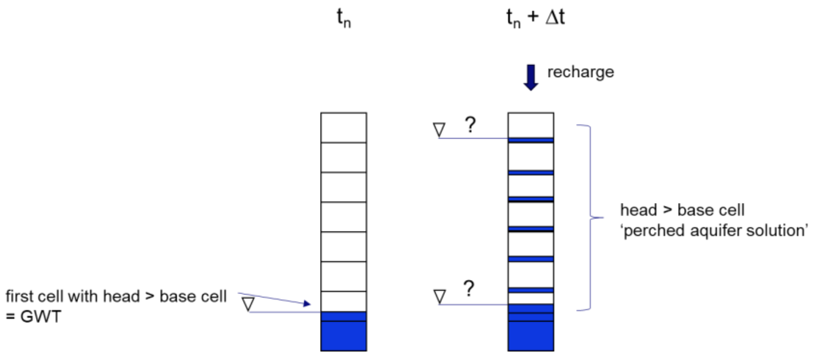

Figure 3-1 Schematic illustration of the (spurious) MODFLOW6 solution at $t_n + \Delta t$, for a time step in which the imposed recharge exceeds the (saturated) vertical hydraulic conductivity, K_v, of the soil between the land surface and the a priori GWT at t_n. Calculation grid-cells are shown as black rectangles. Blue represents (saturated) groundwater; white represents dry soil. In MODFLOW, a cell is fully saturated when the head exceeds the cell top and partially saturated, with an internal GWT, when the head is between the cell base and the cell top. When recharge exceeds the vertical hydraulic conductivity, the latter condition occurs in the entire cell stack with the low K_v. This solution conceptually approximates a stack of perched aquifers.

3.1.3 Implications

The findings regarding issue 2 demonstrate the limitations of the MODFLOW6 code to generate meaningful solutions when recharge/infiltration is imposed and exceeds saturated vertical hydraulic conductivity in the unsaturated zone. Limiting imposed recharge based on K_v can be an option but is not trivial when the unsaturated zone is vertically heterogeneous as occurs in soil profile C (Figure 2-1). Moreover, even when the 'proper' MODFLOW solution is obtained when imposed recharge does not exceed K_v, and all the water is transferred to the phreatic groundwater, the solution still remains rather poor since it neglects changes in soil moisture storage in the unsaturated zone. Resolving the latter issue is a specific task (M2) set in this report (paragraph 1.2). Issue 2 is, therefore, better tackled via tasks M2 and M1, which call for improved representation of unsaturated zone processes in the modelling.

3.2 Expert opinions on the general approach

For task P2, experts at different institutes were contacted to seek their opinions on the approach outlined in the interim report [1]. Opinions were obtained from the persons listed in Table 3-1. Paragraph 3.2.1 presents a summary of the opinions drafted by the authors of this report. The original communication documents, which were received as annotated versions of the interim report, email texts and separate reports, some in Dutch, others in English, are not included, but could be made available on request, pending authorization by the experts. The experts have been provided with and have expressed agreement with the summary (paragraph 3.2.1) and the formulated implications thereof for the project (paragraph 3.2.2).

Table 3-1 Participating experts

Expert	Affiliation	Expertise
MSc H. Bootsma	Deltares, Unit subsurface and groundwater systems	Groundwater modelling and software development
Dr. V.E.A. Post	Edinsi Groundwater	Groundwater modelling and software specialist
MSc D. van de Craats	Wageningen Environmental Research, subdivision Soil, Water and Land Use	Soil, water and land use

3.2.1 Summary of feedback

The experts expressed general support for the adopted approach; the general approach is referred to as “defensible”, “yields useful insights” and “workable/practicable”. The experts also confirmed the concerns/considerations and needs for improvement that were raised in the interim report [1] and that provide the focus of the work presented in this report:

- The need for improved unsaturated zone processes representation.
- The unrealistic nature of the peaks in the GWT response to precipitation events.
- The need for more extensive sensitivity analysis.

Specific remarks and recommendations that were provided include:

1. For the province of Groningen, the used regional head difference (with respect to the polder-/ditch SWL) of 4 m is excessive.
2. How would ‘impact table users’ have to judge the applicable regional coupling?
3. What if the regional (surrounding area) SWL is (also) changed?
4. Impact factors > 1 are implausible; likely to disappear with improved unsaturated zone process representation.
5. In the interim models, water uptake from the GWT by evapotranspiration is unlimited, leading to unrealistically deep GWTs. Example figures are provided for the maximum water uptake (flux) for specific GWT depths (depth w.r.t. the base of the root zone) and its rapid decline with increasing GWT depth. The figures are gleaned from the soil classification scheme for the Netherlands (BOFEK).
6. Similarly, an example calculation is provided for the strong dependency of phreatic storage, S_y, on GWT depth, using representative soil water retention characteristics (Van Genuchten parameters) for sand and clay.
7. Perhaps a code that can handle partial saturation (e.g. Hydrus) would be more appropriate. The drawbacks though are that such codes are plagued by numerical difficulties, excessive runtimes and that the number of model parameters would increase significantly (especially if also the role of the vegetation would be taken into account). A hybrid approach might be a suitable compromise, much like what is done within the context of the NHI (The "Nederlands Hydrologisch Instrumentarium" (Hydrological Instrumentations of the Netherlands)) in which MetaSWAP is used to select the appropriate recharge rate for a given water table depth and soil profile.
8. Study water balance components of models to assess plausibility.
9. Impact factors. Consider including probability of exceedance curves (i.e. showing the percentage of time that a certain GWT depth is exceeded, much like a flow duration curve for streams). Condensing the results into single numbers can be achieved by using percentile values, or the GWT for a given percentile. Such a presentation of results may be less intuitive for non-experts. Hence, they may not necessarily replace the current tables with impact factors but be included in the report in addition.

3.2.2 Implications

The feedback indicates that the general approach is sensible and does not require adjustment. Also, the tasks set for the current report/work are appropriate. Specific remarks and recommendations are evaluated as follows, where the numbering refers to the numbering in paragraph 3.2.1:

1. The used head difference of 4 m relative to the reference polder SWL was adopted to reflect rather extreme SWL differences in the Netherlands, at deep polders, which predominantly occur in the province of Zuid-Holland. The differences in the northern provinces indeed are much smaller. The extremes were chosen to document sensitivity of the regional coupling, and to provide a fairly generic framework that is not limited to the latter provinces. However, somewhat smaller differences would suffice and are adopted in the present report (paragraph 5.1.4).

2. Judgement of regional system coupling in practical use is one of a broader set of questions regarding practical use of the intended tables. These questions merit addressing in a separate ‘user guide’. In general, site-specific information on SWLs and distance from the ‘regional SWL’, often outlet canals or lakes, can be used to judge if the neutral, or the end-member classes ‘high head’ or ‘low head’ would apply. If available, comparison of phreatic and aquifer hydraulic head time series for the aquifer provides valuable information about applicable conditions. If little is known, information from multiple tables can be weighed to judge the range (uncertainty) of possible impacts.
3. Scenarios where the regional head also changes indeed are absent in the current setup. The limitations of use should be clear. In case judgment would also be required for such scenarios, the framework may be extended with additional tables.
4. The intended model improvements should clarify if impact factors > 1 are still predicted.
5. The elucidated concepts and datasets of soil physical properties provide valuable elements for the intended model improvements.
6. As point 5.
7. Apart from the mentioned numerical issues, the Hydrus code [5,6] was not considered for the project because, as a separate code, it does not allow addressing the coupling with the regional (ground)water system as implemented in the current approach. The coupling is (expected to be) a key factor that determines the SWL lowering impact. Moreover, as a separate code, Hydrus does not support confined water storage (specific storage in MODFLOW), which results in unrealistic quasi-steady state groundwater flow fields and instantaneous adjustment to boundary condition changes[7]. Confined storage exerts an essential control on (diffusional) delays in pore pressure and hydraulic head propagation and buffered interaction between the phreatic GWT and the hydraulic head of the deep aquifer. MetaSWAP [7,8,9], by contrast, provides a promising option for many reasons. For one because it is a separate (unsaturated zone) model, which, as mentioned, has been coupled with MODFLOW in NHI. Moreover, as explained in paragraph 4.2, MetaSWAP includes a fairly complete unsaturated zone water transfer representation that implements the concepts of points 5 and 6 above. And MetaSWAP can be parameterised using the national datasets mentioned in points 5 and 6. More details are provided in Chapter 4.
8. Implausible water balance terms can only pertain to excessive water loss from the ditches to the deep aquifer, or excessive gain by the ditches and drains due to upward seepage from the deep aquifer[8]. The largest water exchange in the models occurs for the strong regional coupling, which includes a low effective resistance (50 days) between the deep aquifer and the regional head. We calculated the exchange in steady state model runs with zero precipitation and evaporation (Table 3-2).
   The inferred seepage rates for soil types A, C and D are reasonable as they are well within the range indicated by the national ‘seepage and infiltration’ map of the Climate Impact Atlas[9].

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[7] Though web-search, it was found that a Hydrus-package exists that can be coupled with MODFLOW. However, this package does not appear available for MODFLOW6 that is used in the present project.

[8] Momentary fluxes derived from the climatic conditions cannot be considered implausible as long as the forcing is realistic.

[9] Seepage rates up to 2 mm/yr prevail. No upper bound is provided, but magnitudes > 5 mm/yr clearly are rare.

Table 3-2 Average vertical seepage (in mm/day) across the Holocene sequence (layers above the deep aquifer) for the interim models for steady state conditions without precipitation/evaporation. Results are for strong-regional coupling.

A		**B**		**C**		**D**	
upward	downward	upward	downward	upward	downward	upward	downward
1,65	1,61	71,29	38,72	2,42	2,38	0,79	0,79

The seepage calculated for soil type B, however, clearly is excessive. Inspection of the interim model results [p. 44; 1] reflects this as well, as the model shows permanent water logging for upward seepage, also during drought. Such settings either require a very high-density drainage system (very narrow parcels and pipe drainage (Horstermeerpolder) or are used as natural wetlands or lakes (with elevated SWL to suppress seepage). Since in such settings SWL lowering is never considered/applied, and the current project focuses on groundwater impacts that are relevant for damage risk of buildings/houses, the seepage rate for soil type B models needs to be reduced in the improved modelling to values that are associated with reasonably ‘dry soils’ a significant part of the year.

9. Additional or alternative measures to quantify the impact of SWL lowering need further consideration (as mentioned in [1]). And the duration of low(er) GWT is relevant in this respect. However, this is beyond the present project and this report.

4 Improved representation of unsaturated zone hydrology

4.1 Shortcomings of the interim modelling

The interim modelling presented in [1] was/is considered insufficient in its representation of the unsaturated zone. Two key issues that were outlined are:

1. *The modelling of (saturated zone) groundwater recharge or loss from precipitation and evapotranspiration.* Input consists of time series of daily precipitation (P) and potential evapotranspiration[10] (E_{pot}). 'Net precipitation' ($P-E_{pot}$), is applied as groundwater recharge through the RCH package of MODFLOW (note that negative recharge represents a dominant water loss by evapotranspiration). Key shortcoming of this approach is that water uptake from the GWT by evapotranspiration is unlimited in the sense that its magnitude equals E_{pot}. In reality, actual evapotranspiration (E_{act}) is suppressed relative to E_{pot} when soil moisture availability in the root zone drops during dry spells and plants cannot transpire optimally. Such conditions are essential for the current project which focuses on the low GWT's that develop during drought. Another shortcoming of this approach is that 100% of positive net precipitation is transferred to the GWT. In reality, when the GWT is deep and the soil dry, a large fraction of this water will replenish soil moisture and will not cause recharge at the GWT. This shortcoming is strongly related to the second issue below.

2. *The modelling of phreatic storage*[11]. In MODFLOW, phreatic water storage occurs in the depth interval between the old and new GWT within a model time step. That is, it is implicitly assumed that change in water saturation only occurs in this interval. And GWT change is modelled using a phreatic storage coefficient (specific yield; S_y) that is assigned to individual model cells and, analogous to hydraulic conductivity, is approached like a material/soil property. In the interim modelling, distinct S_y values were, for instance, assigned for sand and clay. A shortcoming of this approach is that it negates the fact that GWT change is typically associated with saturation (soil moisture) change up to the land surface, above the (old and new) GWT. The phreatic storage coefficient, therefore, is better approached as an integral property, which changes fairly gradually with GWT depth. The oversimplified MODFLOW approach may cause unrealistic GWT changes.

4.2 Improved representation with MetaSWAP

To address the shortcomings, the modelling was extended using the unsaturated zone capabilities of MetaSWAP. MetaSWAP was chosen for several reasons:

- It can be used in conjunction with MODFLOW
- Code, coupled with MODFLOW6 (used in interim modelling), is directly available from the NHI (maintained by Deltares)
- It provides a consistent framework to address both shortcomings of paragraph 4.1.
- It should also resolve the spiked response behaviour (issue 2, paragraph 3.1.1).
- Parameterisation can benefit from an existing national dataset for soils in NL.

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[10] Reference crop-evaporation according to Makking.

[11] This is storage associated with GWT change due to change in saturation of subsurface layers.

More detailed information on MetaSWAP is provided in the following paragraphs.

4.2.1 MetaSWAP

MetaSWAP is a code, developed at Wageningen University & Research, for 1D (vertical column) modelling of unsaturated zone soil water dynamics and water transfer [7,8,9]. The code is specifically designed for coupling (via multiple parallel columns) with the saturated groundwater flow model code of MODFLOW. MetaSWAP is a quasi-steady state model in that sequences of steady-state solutions of the Richards' equation are used to efficiently perform dynamic simulations (Figure 4-1). Coupling with MODFLOW is based on the shared state variable 'phreatic groundwater level' (= GWT = h in Figure 4-1) and involves an iterative scheme for the phreatic storage coefficient. The water balances for each MetaSWAP column are made at the aggregate scale of two control boxes that are shown in Figure 4-2: the root zone and the 'subsoil'. However, the continuous moisture and pressure head profiles are available 'on the background' and can be construed/mapped at all times[12].

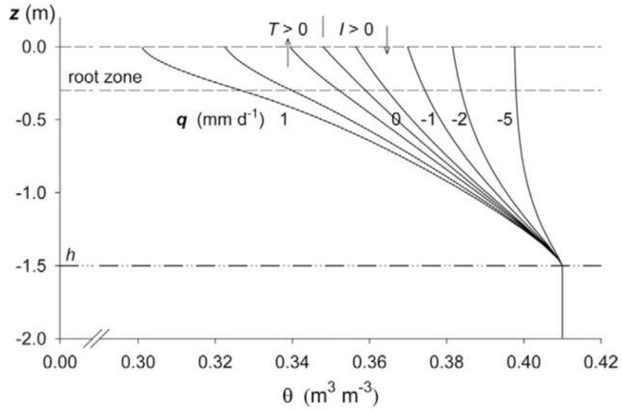

Figure 4-1 Examples of steady-state profiles for a loamy soil with a root zone thickness of 0.3 m and a GWT elevation of -1.5 m. θ is volumetric water content. For the capillary rise profiles (transpiration rate T>0) the given values of the flux density (q>0) are for below the root zone; for the equilibrium profile and the percolation profiles (infiltration rate I≥0) the given values of the flux density (q≤0) are for the whole profile down to the GWT. The flux density q represents the groundwater recharge/loss at the GWT due to precipitation and evapotranspiration. Each profile is also associated with a steady-state profile of the pressure head (not shown). Source: [7].

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[12] In this sense MetaSWAP is not a simple lumped (coarsely discretised) parameter model.

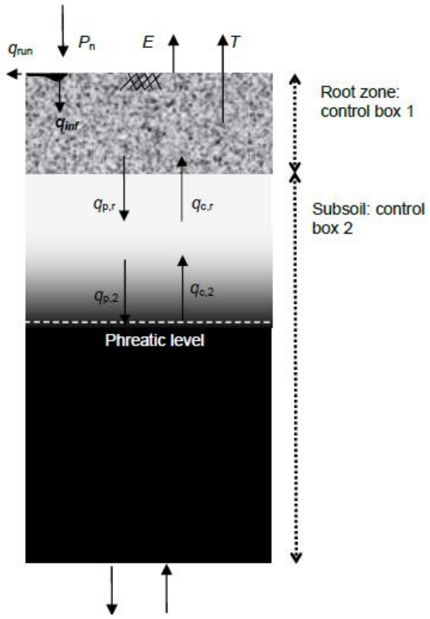

Figure 4-2 The two control boxes used in the water balance calculation and associated flows. Explanation of symbols: P_n *– precipitation (at ground surface);* q_{inf} – infiltration; q_{run} – surface runoff; E – evaporation of bare soil; T – transpiration; q_p – percolation; q_c – capillary rise. *Source [9].*

In a preprocessing step, a large set of steady-state solutions is computed for the employed soil profile (layer stack of soil types) and root zone depth for a very large range of (i) potential boundary flux values for the root zone and (ii) GWT depth. These steady states are calculated with SWAP [10], which is 'the Wageningen code' for non-steady unsaturated zone simulation. Actual transpiration (water loss by root uptake) is reduced relative to the potential values as part of the solution when the root zone moisture content (and pressure head) declines. The steady states are stored in tabular form using the aggregate-level (root zone and subsoil) variables. The table is used in the subsequent MetaSWAP calculations[13]. MetaSWAP has been extensively verified and validated (performance compared with SWAP) [e.g., 7,11][14].

4.2.2 Code modification of MetaSWAP-MODFLOW6 coupling

A MetaSWAP-MODFLOW6 modelling tool, maintained by Deltares, was available from the NHI[15] at the start of this project. However, the way the coupling was coded, proved unsuitable for the way the parcel-scale models were set up in this project, using small vertical cell heights (0.05 m) and the 'non-standard' Newton-Raphson method[16] for the formulation of the algebraic model equations. The latter choices were made to achieve desired detail in resolving head fields and flow, notably close to the water courses. In this setup, the GWT moves up and down to higher and lower model cells. The coupling in the available tool was coded for more conventional model setups in which the GWT variation stays within the top MODFLOW model cell, an approach that is typically used in modelling of large spatial domains. To allow use of MetaSWAP for the current project, the coupling was recoded to ensure that MetaSWAP couples with the GWT-containing cell, both in model time steps and in the iterative scheme.

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[13] 'Meta' of MetaSWAP refers to the use of this aggregate scale information derived from SWAP.

[14] Validation entails comparison with equivalent SWAP models; these are single-vertical column models. Explicit validation for coupling with spatially extensive groundwater models does not exist.

[15] The "Nederlands Hydrologisch Instrumentarium" = Hydrological Instrumentations of the Netherlands.

[16] The Newton-Raphson method has many advantages for GWT problems like those addressed here, and will often converge when the standard formulation fails to converge due to difficulties associated with (re)wetting and drying of cells.

4.2.3 National database of soil physical properties

Both for site-specific applications and generalized modelling - the latter applies to the current project -, soil parameters for MetaSWAP are commonly obtained from the national Staring series of soil physical property types [12]. This series contains parameters[17] for 18 different 'uppersoils' (referring approximately to the root zone) and 18 subsoils. Subsoils, for instance consist of classes of sand (7), silt (3), clay (3), loam (2) and peat (3), where the number in brackets are the number of classes. The classes are referred to as building blocks, indicating that layers of these classes can be combined in a stack to generate general soil profiles. The Staring series provide nationwide coverage of all soil units that are distinguished in the national soil map of the Netherlands that is registered in the BRO (Basisregistratie Ondergrond) and also provide the basis for the national soil physical unit map (BOFEK) [15]. In the available MetaSWAP-MODFLOW6 tool, pre-processed (tabular) input (see paragraph 4.2.1) is available for the 79 BOFEK soil profiles (units). This database can be extended with input for tailor-made soil profiles with a preprocessor, where both layering and the default soil parameters of the Staring series can be altered.

4.3 'Validation'

This paragraph presents results for the validation task V1 (see paragraph 1.2). This task aims to provide support for the modelling approach, by demonstrating that the MetaSWAP-MODFLOW6 approach yields plausible GWT predictions for relevant soil profiles and boundary conditions[18]. 'Validation' is put in quotation marks in the section heading to indicate that the term does not imply comprehensive or exhaustive proof of adequacy of the modelling[19], but rather an inherently limited performance testing against observational data. This is done by comparing model-predicted and available monitored GWT time series. Because usable GWT time series for SWL-lowering are not available, the comparison is limited to selected 'normal' GWT time series for stable SWL. Hence, 'validation' is only performed for stable SWL. 'Validation' for SWL lowing is not possible due to lack of data.

4.3.1 Site selection

To carry out a meaningful comparison, site-specific conditions need to be well known, as differences in behaviour between model and observations can readily reflect influences of factors that are insufficient known rather than deficiencies of the modelling tool.

Criteria used in the selection of time series include:

- The time series provide a good approximation of the phreatic level (GWT). 'Shallow' groundwater observation wells often have a filter which partially penetrates a shallow aquifer underneath a cover layer and, therefore, record a hydraulic head which may not be representative of the phreatic GWT. This applies specifically to type B and type D soil profiles.
- The soil profile is clear.
- The observation well is located away from ditches and roads ('mid parcel'). This limits influences by unknown factors.
- The SWL relative to the land surface can be judged.
- The time series is > 5 year and of sufficient resolution to reflect varying climate/weather conditions.
- The well is located in a rural setting to limit unknown effects of pipe drains, leaky sewers, and complex surface properties affecting infiltration and evapotranspiration. This is particularly relevant for type C profiles.
- Clarity regarding coupling with regional (ground)water system.

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[17] Soil water retention parameters [13] and unsaturated zone hydraulic conductivity parameters [13,14].

[18] The general usefulness /capability of the tool to model GWTs has been ascertained in numerous studies.

[19] Some scientists have argued that validation of numerical models of natural systems is impossible [20].

Site search was done using the national subsurface data and information system Dinoloket. Additionally, available data and reports of the experimental field site KCT Zegveld in the peat meadow area of Utrecht (province) were studied.

The KCT Zegveld location meets most criteria, but was not selected for modelling for two reasons. One, on parts of the monitored parcel(s) tests are conducted with steered drainage systems, and it cannot be ruled out the other wells are not influenced by the tests. Two, although there are ample ‘other wells’, only spatially averaged GWT time series of multiple wells at various distances from the ditches were available.
In Dinoloket, two usable sites were found, one near Termunten, Groningen (well B08A0153-001) and one near Mantgum, Friesland (well B10F0085). The wells are in a comparable setting with a thick clayey sequence which corresponds to soil profile type A (Figure 2-1). The well at Termunten was selected for the modelling because the higher resolution time series (twice a month, compared to bi-monthly at Mantgum).

4.3.2 Selected site

Figure 4-3 shows the well location and the GWT time series. The well is located in the centre of 60 m wide parcel, in close proximity to the Waddenzee (500 m). The GWT time series covers the period 1961 to 1972 and consists of measurements at the 14th and the 28th day of the month.

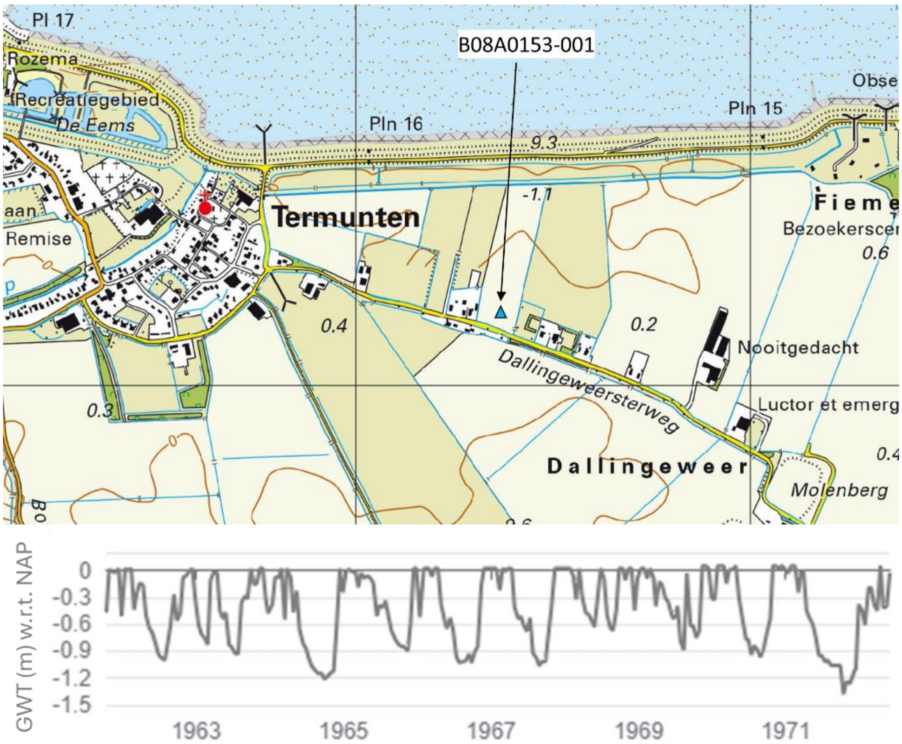


Figure 4-3 Top: map of the Termunten area. The well location is indicated with a blue triangle. The Waddenzee is visible in the uppermost part of the map. Bottom: GWT time series of the well. The (historical) land surface elevation is about +0.1 m NAP.

Geological data in Dinoloket (BRO GeoTOP v1.6 model) show a clay-rich sequence to 10 m below land level which overlies a 10 m thick sandy aquifer. At shallow levels, a thin peat layer occurs. The lithological description of the borehole that was drilled for well placement (to about 2 m below land level) shows clay on top of 0.3 m of peat (Figure 4-4). According to the BRO Bodemkaart 2023 – this is the national soil map in Dinoloket –, the soil to 1.2 m depth is categorised as a clayey silt (soil type Mn15C).

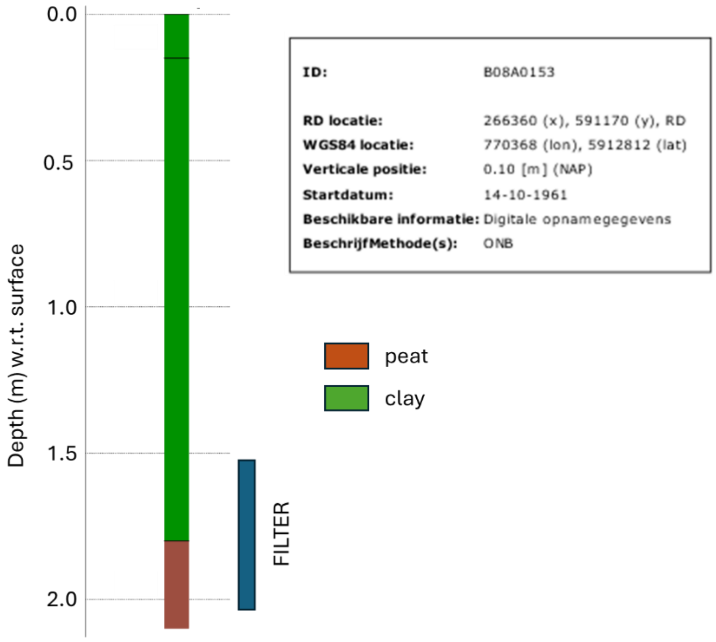


Figure 4-4 Lithological description of the observation well borehole. The filter position of the well is also shown.

The applicable SWL in the fixed water level area is not accurately known. However, based on the historical ‘waterstaatskaart’, the SWL around the mid-1970s is estimated at about -1.5 m NAP. The land surface (0.1 m NAP at the time of well placement), is unlikely to have changed significantly; land subsidence due to gas production at this location has been very limited (about 0.06 m in 2020 [16]).

Upward seepage conditions are likely to exist due to the higher head (0 m NAP) of the nearby Waddenzee. Due to the rather thick confining clay layer (~10 m), the regional coupling of the aquifer with the Waddenzee is probably weak (large resistance in between).

4.3.3 Model setup and parameterisation

Model design and parameterisation is virtually identical to that used in the generic modelling. For details, the reader is referred to paragraph 5.1. Here, only site specific adjustments/choices are explained.

The parametrisation corresponds to that of soil profile type A with adjustments/choices for:

- *The MetaSWAP soil type.*
  A moderately clayey silt (Staring series soil O09) was used. This is the prime constituent of the ‘bodemkaart soil type’ Mn15C.
- *The ditch water level (SWL).*
  A base value SWL = -1.5 m below ground level was chosen. Sensitivity to a slightly higher SWL of -1.0 m below ground level is also studied.
- *Regional head and regional coupling.*
  A base value regional head = 0 m relative to ground level was chosen (Waddenzee). A base choice of weak regional coupling (1000 days resistance in the GHB boundary condition). Sensitivity to a slightly lower head of -1 m relative to ground level was studied (with a weak regional coupling) as well as the sensitivity to a strong regional coupling (10 days resistance in the GHB boundary).
- *Climate forcing.*
  Precipitation and reference crop evaporation data from the weather station Eelde was used. This is the closest KNMI weather station to the borehole (about 50 km

away; south of the city of Groningen) with daily records which overlap with the measured time series. Data for this station is available between 1965 to 1972.

4.3.4 Results

Figure 4-5 displays the model-predicted GWT time series and the observational data. The blue curve (coded: -1.5_0_1000) represents the a priori 'best guess' conditions for the site. The correspondence with the measurements is excellent considering no calibration or optimisation was done, and considering the meteorological data used in the modelling is from a distant location (Eelde). Good correspondence is also observed for a higher ditch water level (-1_0_1000) and strong regional coupling (-1.5_0_10). The simulation with a lower regional head (-1.5_-1_1000) tends to overestimate the seasonally low GWT relative to the land surface.

The fact that the measured GWT is capped at about 0.1 m below the land surface presumably reflects the well head being placed below ground level, with the well tube rim at 0.1 m below the land surface.

Overall, the results support the MetaSWAP-MODFLOW6 approach.

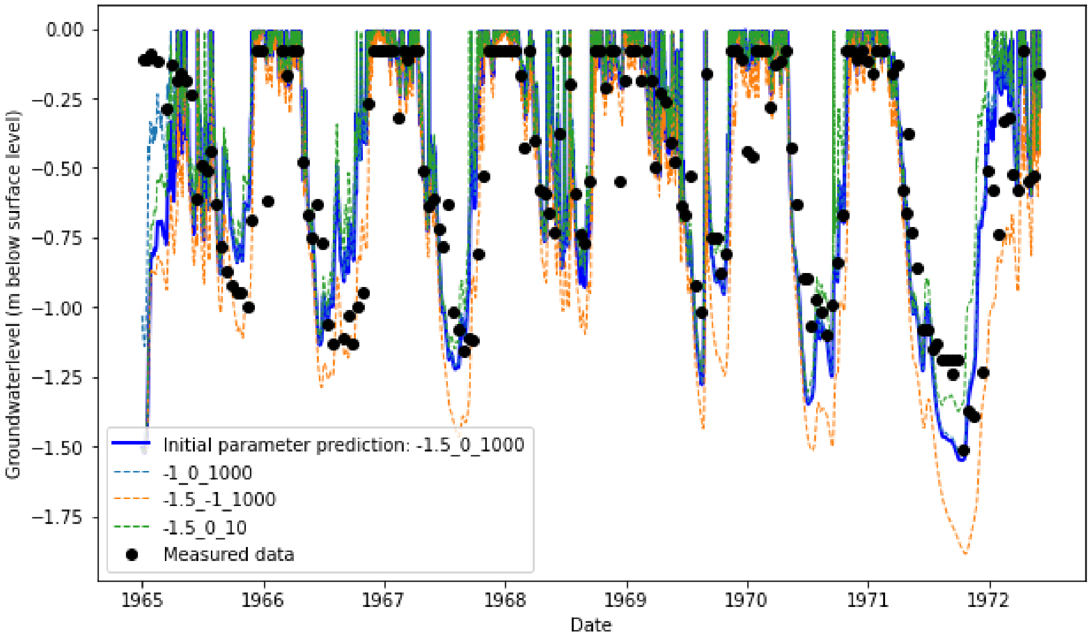


Figure 4-5: Comparison of MODFLOW-MetaSWAP predicted and observed GWT time series for the groundwater observation well B08A0153-001 near Termunten, Groningen. The measurement error associated with the observations is typically a few centimetres. The three-number code in the legend for the modelled time series has the following meaning: the first value represents the SWL (relative to surface level), the second value represents the regional head (relative to surface level) and the third value represents the regional coupling (either a weak coupling: 1000 days resistance in the GHB, or a strong coupling: 10 days resistance in the GHB).

5 Calculated model variants

This chapter introduces the design and parameterisation of the base set model variants (paragraph 5.1), and the variants thereof that are used for the sensitivity analysis (paragraph 5.2).

5.1 Base set

5.1.1 Domain and boundary conditions

The general features of the model design are shown in Figure 5-1 and Figure 5-2. The domain extends between the middle of two parcel-bounding ditches. The lower 5 m of the domain represents the (extensive) aquifer. The land surface is chosen at z = 0 m to facilitate the interpretation of the results.

The same parcel width (~ 60 m) is used for the four soil profiles A-D to bring out the different responses of these profile types. Smaller parcel widths occur in peat meadow areas where high surface water levels are maintained (low freeboard). Larger parcel widths are common in areas with arable farming, often in combination with pipe drains. The adopted width, therefore, represents an intermediate value. A 2 m deep and 2 m wide ditch was chosen – the ditch itself is not part of the model domain (no hydraulic head calculation). The dimensions allow both for a reasonable freeboard (~1 m) and a reasonable water depth. The latter also allows for some ditch water level lowering. Although calculations are done for a single parcel, the symmetry ensures that the results are representative of SWL lowering over a more extensive domain involving multiple parcels and bounding ditches.

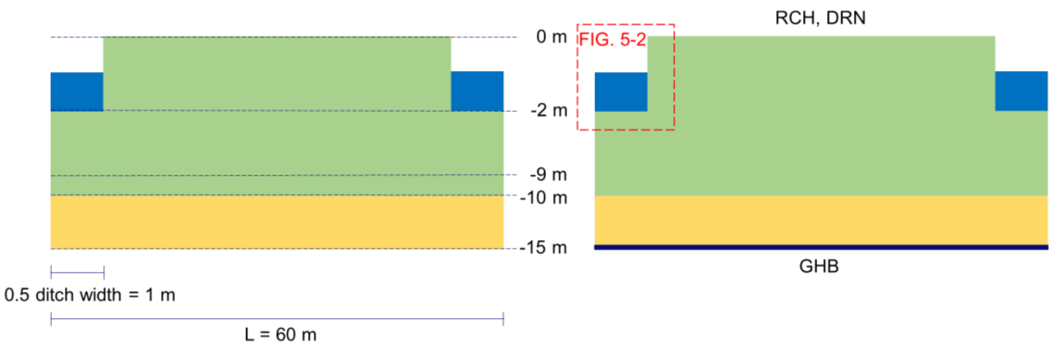
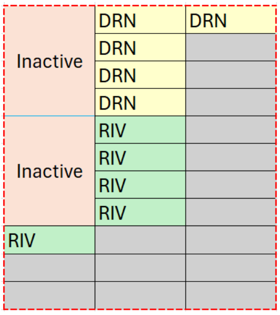


Figure 5-1: General features of the 2D cross-sectional model design (not to scale). Left: model domain. The left and right boundary correspond to the middle of the parcel-bounding ditches. The dashed lines indicate the vertical levels used to define the boundaries of the soil layers of the four soil layer profiles A-D. Right: types of boundary conditions. The lateral boundaries are closed to groundwater flow. The recharge boundary (RCH) at the top is used to impose the climate regime. The top drain (DRN) boundary condition is used to model surface water runoff in case the GWT tends to rise above the land surface. The general head boundary condition (GHB) at the base of the model is used to model the regional influences via coupling with the aquifer. The inset refers to the figure in which the boundary conditions used at the ditches is shown.



Inactive	DRN	DRN
	DRN	
	DRN	
	DRN	
Inactive	RIV	
	RIV	
	RIV	
	RIV	
RIV		

Figure 5-2: Boundary conditions used to simulate the surface-groundwater exchange at the ditches (zoomed in part of the cross section shown in Figure 5-1). Below the ditch water level (blue line), river boundary conditions (RIV) are used. This ensures realistic inflow from ditch water in case bounding cells become unsaturated during drought and allows parameterisation of ditch bottom resistance. Drain boundary conditions (DRN) are used above the ditch water level to allow outflow of groundwater during high GWT in the ditch wall (seepage face), while no inflow can occur for these cells.

5.1.2 Discretisation

The horizontal and vertical cell size are, respectively, 1.0 m and 0.05 m. The fine vertical discretisation supports high resolution tracking of the GWT and prevention of spurious lateral groundwater flow in the unsaturated zone which changes continuously in space and time. The fine vertical discretisation also allows representation of outflow of saturated groundwater in the ditch wall above the ditch water level (seepage face) via the DRN-boundary condition (Figure 5-2) when the GWT is above the SWL at the ditch wall. The horizontal cell size of 1 m is the smallest practical size in the MODFLOW-MetaSWAP coupling. Grid convergence testing – this can be used to demonstrate that the inferred impact factors are robust against grid refinement – was not conducted. However, it is reasonable to assume that the effects of the 1 m horizontal discretisation are negligible beyond a few meter from the ditches.

Adaptive time steps were used in the model variants. This is a MODFLOW6 method that determines the appropriate time step length. If a time steps fails to converge, MODFLOW attempts to correct the problem by reducing the time step. Alternatively, MODFLOW is also able to increase the time step length if a time step is solved very easily.

5.1.3 Initial conditions

The starting hydraulic heads were set equal to the modelled ditch water level (SWL). The precipitation surplus in the initial timestep was set to zero.

5.1.4 Parameterisation

Climate

Because building damage risk is associated with low GWT conditions, the climate regime of 2018, one of the driest years on record in The Netherlands, was chosen to force the model[20]. Daily precipitation and potential evaporation data for the De Bilt weather station were collected from the KNMI and used as input for MetaSWAP (Figure 5-3). Three years were simulated in which the 2018 climate record was repeated three years in a row. This was done because a single year simulation might yield spurious effects originating from the initial condition not having equilibrated to a temporally varying climate. The GWT time series for the third year was used in the analysis.

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[20] This approach was also taken by CMA (1987) [3] where the dry year record of 1976 was used.

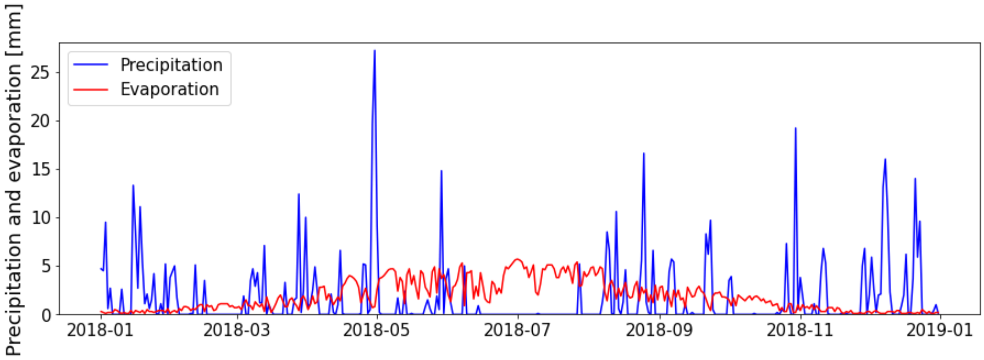


Figure 5-3: Top: daily precipitation and potential evaporation measured at the De Bilt weather station during 2018. This is used as input for MetaSWAP.

MetaSWAP parameters

As MetaSWAP is a Meta-model, many soil characteristic parameters are included via the database. This database contains the results of SWAP simulations which use the parametrization and discretisation from the national Staring series. For soil profiles A, B and D, a O12 soil was chosen, which represents a medium heavy clay. For soil profile C, a O07 soil was chosen, representing a loamy soil with very fine to moderately fine sand. The soil properties associated with each profile can be found in [15].

In MetaSWAP evapotranspiration is simulated using four different terms:

- crop transpiration,
- canopy interception evaporation,
- soil evaporation,
- ponding evaporation.

For the crop transpiration, a simple evapotranspiration model was used. This concept uses crop factors and Makkink reference evaporation to compute the potential transpiration per crop type. Since grass is used as landcover, a crop factor of 1 was used. The interception capacity of grass was set to zero, which means no canopy evaporation was simulated. The soil cover was set to 100% which means no bare soil evaporation was simulated. The ponding level was set to zero, which means no ponding, and therefore no ponding evaporation, was simulated.

The potential transpiration therefore only consists of crop transpiration. The actual transpiration is computed using the Feddes function [19]. This uses a reduction coefficient for root water update as a function of the pressure head in the rootzone and the potential transpiration rate [9]. A rootzone depth of 30 cm was used. The used Feddes parameters are listed in Table 5-1.

Table 5-1 Feddes parameters used in MetaSWAP

p1	99
p2	99
p3h	-2
p3l	-8
p4	-80
t3h	5
t3l	1

In case of drought, irrigation of crops can be simulated when the pressure head in the rootzone falls below a threshold value. In this case irrigation was disabled.

Hydraulic properties of model layers (MODFLOW)
Figure 5-4 depicts how the four model layer types listed in the legend are used to characterize the four archetypal soil profiles A-D. The model layer types were assigned characteristic parameter values listed in Table 5-2, where K_h and K_z respectively denote the horizontal and the vertical hydraulic conductivity, S_s is specific storage[21]. Specific yield (S_y) is not listed since it is a calculated parameter in the coupling with MetaSWAP.

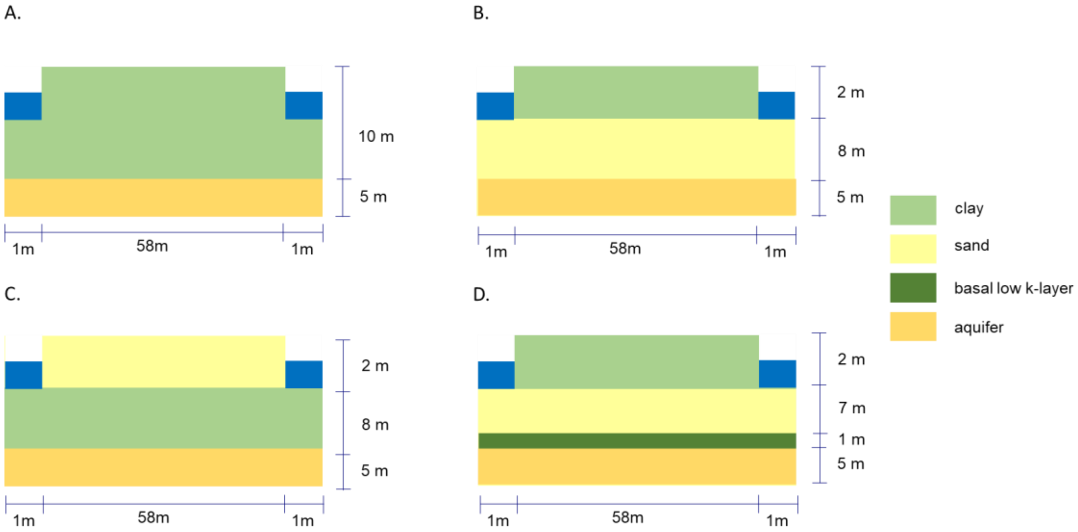


Figure 5-4: Thicknesses of the model layers and model layer types (legend) for the four archetypal soil profiles A-D. Note the thickness are not shown to scale.

The contrasts of hydraulic conductivity of the model layer types are more important than their precise individual values. The relatively high specific storage of clay reflects the characteristic high elastic compressibility of Holocene clays which mainly works to slow vertical propagation of hydraulic head changes through the clay layer. The horizontal hydraulic conductivity of clay in the top 50 cm of the soil is assigned a (much) higher value than deeper clay. This represents the influence macropores due to shrinkage cracks, tillage and burrowing that typify shallow clay soils. The “korte klei”, which occurs widely in the province of Groningen is a well-known example. It should be noted that the high horizontal conductivity only enhances lateral conveyance of soil water when fully saturated; above the GWT no horizontal flow occurs as water transfer is solely vertical in MetaSWAP.

Table 5-2: Hydraulic parameters assigned to the four model layer types.

Hydraulic parameter **Soil type**	**K_h (m/d)**	**K_z (m/d)**	**S_s (1/m)**
Clay top 50 cm	1	5e-3	5e-3
Clay below 50 cm	5e-3	5e-3	5e-3
Sand	5	2	1e-5
Basal low K-layer	2e-4	2e-4	1e-5
Aquifer	100	100	1e-5

---

[21] Storage property that applies to head loss or gain when the soil remains saturated (below the GWT). Defined as water volume change per unit soil volume per unit head change.

Land surface drainage boundary condition
(DRN)
The model cells in the top subsurface layer are modelled as *drain* cells for which:
Drain elevation is set to 1 cm below surface level.
Conductance is set to 10 m^2/d for all cells in the top row.
This prevents the GWT to rise above the land surface in the calculations.

Ditch boundary conditions
(RIV)
Below the ditch water level, model cells bordering the ditch are modelled as *river* cells (Figure 5-2) and require three model parameters: *stage (m)*, *river bottom (m) and conductance (m^2/d)*. *Stage* is assigned the desired ditch water level. For cells below the ditch bottom*, river bottom* is assigned the ditch bottom level. In the present simulations, *river bottom* = -2 m (Figure 5-4).
For cells adjacent to the ditch water, *river bottom* is assigned the level of the centre of the cell. *Conductance* is parameterised using an adopted water bottom resistance C_{wb}. In the present simulations $C_{wb} = 1$ *d. Conductance* = A/C_{wb}, with A *(m^2)* the surface area of the cell face through which the flow occurs.
(DRN)
Above the ditch water level, model cells bordering the ditch are modelled as *drain* cells (Figure 5-2) and require two model parameters: *drain elevation* (m) and *conductance (m^2/d)*. *Drain elevation* is assigned the level of the centre of the cell. *Conductance* is determined by the flow resistance experienced along the path from the middle of the cell to the ditch wall. This is quantified as *conductance* = K_h x A / L, where L is half the horizontal cell size and A the surface area of the cell face through which the flow occurs in the ditch wall.

Ditch water level
Three ditch water levels are used to study the impact of SWL lowering:

1. SWL = -1.0 m (reference level)
2. SWL = -1.2 m
3. SWL = -1.5 m

Aquifer boundary condition; regional influences
The coupling of the parcel groundwater with the regional hydrological system (Chapter 2) is modelled by applying a *general head boundary* (GHB) at the base of the modelled aquifer (Figure 5-1). GHB requires two model parameters: *boundary head* (external to the model domain) and *conductance*. Boundary head here represents the regional head. The conductance was specified based on an equivalent resistance, which does not scale with the size of the cell. The regional head and resistance used for the six regional influence classes are listed in Table 5-3. The conceptual meaning of the six classes is described in Table 2-1.

Table 5-3: GHB parameters for the six classes of 'regional influence'. The boundary head (=regional head) is given as a difference (bold) relative to the reference ditch SWL (-1 m). The difference for soil profile B is smaller than for soil profiles A, C and D.

'regional' head coupling	**high**	**neutral**	**low**
strong	Regional head: A, C, D: -1 **+ 3 m** B: -1 **+ 0.5 m** Resistance: 10 d	Regional head: A, C, D: -1 **+ 0 m** B: -1 **+ 0 m** Resistance: 10 d	Regional head: A, C, D: -1 **- 2 m** B: -1 **- 0.5 m** Resistance: 10 d
weak	Regional head: A, C, D: -1 **+ 3 m** B: -1 **+ 0.5 m** Resistance: 1000 d	Regional head: A, C, D: -1 **+ 0 m** B: -1 **+ 0 m** Resistance: 1000 d	Regional head: A, C, D: -1 **- 2 m** B: -1 **- 0.5 m** Resistance: 1000 d

The differences of the regional head relative to the reference ditch SWL (shown in bold in Table 5-3) are smaller than the differences used for the interim models (+4 m and -4 m). The differences were reduced for several reasons:

- The consulted experts judged the differences to be rather extreme (point 1 in paragraph 3.2). Differences larger than 3 m are rare and do not occur in the northern provinces that are of particular interest in the KEM research program.
- For soil profile A with strong coupling, the model could not be completed with the imposed closure parameters for differences of -3 m or more (lack of iterative convergence within individual time steps and too large water balance errors). To allow proper intercomparison of the impacts for the low regional head runs, a difference of -2 m was adopted for all runs.
- For soil profile B, the regional head differences relative to the polder SWL were reduced to the much smaller value of 0.5 m. This was done to reduce the excessive vertical seepage in the interim models for soil profile B (point 8 in paragraph 3.2). The upward and downward seepage for the applied head difference of +0.5 m and -0.5 m is 10 mm/d. Upward seepage of this magnitude does occur, for instance, in the Horstermeerpolder in the province Noord-Holland [16].

5.2 Variants of the base set

Task M3 (paragraph 1.2) aims to determine the sensitivity of the impact factors (of the base set) to various conditions. For this task, the following modifications were applied to the base set.

(1) Climate forcing with 2016-2018 meteorological conditions

This variant answers the question if weather conditions in the year(s) preceding the year of drought affect the impact factor for the year of drought. The climate record of meteorological station De Bilt was used.
This variant is applied to all base set model.

(2) Double width of the parcel bounding ditches

This variant sheds light on the influence of the width of parcel bounding water courses on the impact factor. The half width of the ditches is changed from 1 m to 2 m.
This variant is applied to all base set model.

(3) Ditch deepening with SWL lowering

In this variant, the SWL lowering of 0,2 m and 0,5 m is combined with lowering of the ditch bottom by the same amount. For relatively large SWL lowering, deepening of the water

courses is often necessary to maintain the functionality of the water courses in the surface water management system.
This variant is applied to all base set model.

(4) Different unsaturated zone sand properties

The water retention characteristics and permeability of sand can vary significantly depending on its texture. In the base models, a fairly loamy (= silty), fine to medium grained sand (Staring class O3) was used. In this variant, a loam/silt poor fine to medium grained sand was adopted (Staring class O1).
This variant is applied to soil type C (only type with top soil sand).

(5) Different unsaturated zone clay properties

The water retention characteristics of clay soils can vary with clay-mineral content. In the base models, a moderately clay-rich (35%-50% soil (Staring class O12) was used. In this variant, a less clay-rich (25%-35%) soil was adopted (Staring class O11).
This variant is applied to soil types A, B, and D (types with ‘top soil’ clay).

(6) Peat instead of clay

In the base set, the Holocene low permeability strata were modelled with clay-type soil properties. This variant answers the question if (low permeability) peat rather than clay yields similar or different impact factors. The (MODFLOW) hydraulic properties assigned to peat are shown in Table 5-4. Unsaturated zone (MetaSWAP) properties are based on Staring peat class O16.
This variant is applied to soil types A and C.

Table 5-4 Hydraulic parameters assigned to peat.

Hydraulic parameter **Soil type**	**K_h (m/d)**	**K_v (m/d)**	**S_s (1/m)**
Peat	2e-2	5e-3	1e-2

(7) Thinner top soil

In soil types B,C and D of the base set, a 2 m thick ‘top soil’ was incorporated with higher (sand) or lower (clay) hydraulic conductivity than the soil below this top soil. Moreover, the thickness of this layer equals the depth of the parcel bounding ditches (measured from the land surface). In this variant, the thickness of this top soil is reduced to 1,5 m.
This variant is applied to soil types B, C and D.

In addition to the above seven factors, parcel width (notably wider parcels) and tile or tube drainage were mentioned in the interim report [1] as factors to include in sensitivity analysis. This was not followed up upon in the present work for the following reasons:

- For the ~ 60 m parcel width used in the study, the parcel centre is located approximately 30 m from each ditch. This is expected to be sufficiently distant from ditches to also be representative for larger distances (and hence, wider parcels).
- Tube drains are normally positioned above the SWL and drain shallow groundwater during wet periods to prevent water logging. These drains are mostly used in arable farming to support (very) large parcels, thereby limiting the density of ditches / water courses. The main difference with parcels without tube drains is that the GWT may be deeper at the onset of a period of drought, which is modelled here. Although this may then also result in a somewhat larger maximum GWT depth (which is used to infer the impact factor), this is not expected to greatly alter the response to SWL lowering.

6 Results

6.1 General

The following results are included in appendices B, C and D:

- *Time series of GWT and aquifer hydraulic for all simulations.*
  For a location close to one of the ditches, at the edge of the parcel (2.5 m from the ditch; average of the cells with centres at 1.5, 2.5 and 3.5 m from the ditch)
  For a the centre of the parcel (29 m from the ditches; average of the cells with centres at 27.5, 28,5, 29,5 and 30,5 from the left ditch)
- *Impact factors calculated for the two SWL lowering magnitudes 0.2 m and 0.5 m*.

6.2 Definition of the impact factor

The impact factor is calculated as the ratio of GWT lowering and SWL lowering:

$$\text{Impact factor} = \Delta GWT_{low} / \Delta SWL$$

where GWT_{low} is the lowest GWT in the 3rd year of the simulation, which corresponds to the dry year 2018 weather conditions. GWT_{low} for the reference SWL and for the lowered SWL generally do not occur at the same moment. In several cases they occur months apart.

6.3 Explanation of the information presented in the appendices

The results are presented in appendices B, C and D.

Appendix B lists GWT_{low} and the impact factor for each simulation. Results for the base set and the variants are presented on separate pages.

Appendices C1 to C8 include graphics of the GWT time series (3rd year). To visualize the impact of SWL lowering, the panels depict the GWT for the reference SWL (-1 m) and the lowered SWLs (-1.2 m and -1.5 m). The hydraulic head in the deep aquifer is depicted as well. The aquifer head is shown for the reference SWL only. The difference between the aquifer head and GWT indicates if upward or downward seepage conditions prevail and the extent to which the aquifer head adjusts to the GWT changes (most apparent for weak coupling).

Appendix D provides an alternative overview of the impact factors of appendix B, where the impact factors are compiled to allow comparison of the base set impact factors and the impact factors of the variants of the sensitivity analysis.

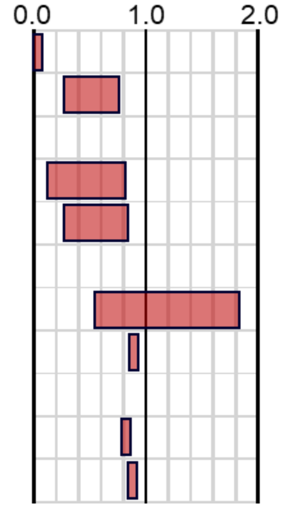
7 Analysis and discussion

7.1 Base set

7.1.1 Characteristics of the impact factors and their controls

The 3rd column in Table 7-1 visualizes the ranges of the impact factors obtained for the centre and for the edge (2.5 m from the ditch) of the parcel for the four soil profiles. Each range shown is based on 12 simulations: 2 SWL lowering magnitudes and 6 variants of regional influence (Table 2-1). Columns 4, 5 and 6 indicate whether or not the impact factor is sensitive to the indicated factors.

Table 7-1 Range of the impact factor for the base set; the check mark symbol indicates sensitivity to the regional head (vertical seepage), the strength of regional coupling (weak/strong) and to the magnitude of SWL lowering..

Soil profile	Position in parcel	Impact factor (range)	Sensitive to regional head (vert. seepage)	Sensitive to regional coupling (weak/strong)	Sensitive to SWL lowering magnitude
					
A	centre		-	-	-
A	edge		✓	-	-
					-
B	centre		-	✓	-
B	edge		-	✓	-
					-
C	centre		✓	✓	✓
C	edge		-	-	-
					-
D	centre		-	-	-
D	edge		-	-	-

Conspicuous differences between the soil profile types are apparent.

Soil profile D. Values close to 1 with little variance are found for soil profile D, both close to and at larger distance from the ditches. The magnitude close to 1 reflects the strong influence of the ditch SWL on the shallow sand underneath the thin cover layer. A lower SWL lowers the head in the sand, which, in turn, lowers the GWT. The small variance is explained by the basal low k-layer, which shields the sand from regional influence via the deep aquifer.

Soil profile B, which differs from D by the absence of the basal low k-layer, shows a large range/variance. This reflects sensitivity to the regional influence via the deep aquifer. Inspection of the tabulated values in appendix B shows that this sensitivity does not pertain to the regional head (upward, downward or neutral seepage conditions), but rather to weak or strong coupling with the regional head. This is indicated by the check mark in the 5th column. Strong coupling, which 'fixes' the hydraulic head in the aquifer, reduces the influence of the ditch SWL on the head in the sand layer. This results in low impact factors. By contrast, weak coupling allows the deep aquifer hydraulic head to decrease in response to a lower SWL and lower GWT. This corresponds to greater sensitivity to the ditch SWL and results in rather high impact factors.

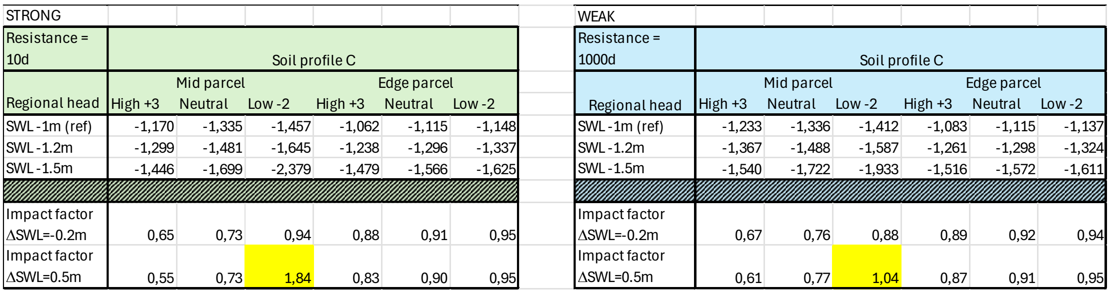
<u>Soil profile A</u> displays impact factor characteristics that differ markedly between the edge and the centre of the parcel. Low impact factors < 0.1, with little variance, are found at the parcel centre. Considerably higher impact factors, showing marked variance, are found at the edge of the parcel. The low magnitude at the centre, reflects the virtual absence of interaction with the ditch water due to the overall low permeability. GWT dynamics at the centre, therefore, is solely governed by the meteorological conditions and vertical seepage across the thick confining layer. Regional influences and the magnitude of SWL lowering then are of no consequence. Close to the edge of the parcel, the connectivity with the ditch water is stronger, resulting in higher impact factors. The relatively large variance at the edge predominantly reflects the influence of upward/downward seepage across the confining layer (shown by the check mark in the 4th column). Upward seepage reduces, and downward seepage enhances the impact factor.

<u>Soil profile C</u>, with the permeable top layer, shows impact factors close to 1 at the edge of the parcel and little variance. The magnitude reflects the strong connectivity with the ditch water. The strong connectivity (stronger than for soil profile A) suppresses regional influences via the deep aquifer, which explains the small variance. At the centre of the parcel, by contrast, the impact factor ranges between 0.55 and 1.84. The large range, and the values in excess of 1 (which may seem illogical), reflect (i) large sensitivity of the water balance at the centre of the parcel vertical seepage, the strength of coupling and the magnitude of SWL lowering (see check marks), and (ii) a reduction in phreatic storage (specific yield S_y) when the GWT drops below the sand layer into the underlying clay. This is explained in more detail in the next paragraph (7.1.2).

7.1.2 Impact factor larger than 1

Table 7-2 lists the impact factors for soil profile C. The table shows that values > 1 (highlighted) are obtained for SWL lowering by 0,5 m and a low regional head (downward seepage). The largest value of 1,84 is found for strong coupling (left table). Strong coupling yields somewhat stronger downward seepage than weak coupling. Figure 7-1 shows profiles of the GWT between the ditches at the moment of lowest GWT for the three SWLs in the ditches. The profiles are useful to explain/understand the high impact factors.

Table 7-2 Excerpt from Appendix B showing results for soil profile C (base set). Impact factors > 1 are highlighted.



STRONG						
Resistance = 10d	Soil profile C					
	Mid parcel			Edge parcel		
Regional head	High +3	Neutral	Low -2	High +3	Neutral	Low -2
SWL -1m (ref)	-1,170	-1,335	-1,457	-1,062	-1,115	-1,148
SWL -1.2m	-1,299	-1,481	-1,645	-1,238	-1,296	-1,337
SWL -1.5m	-1,446	-1,699	-2,379	-1,479	-1,566	-1,625
▨	▨	▨	▨	▨	▨	▨
Impact factor ΔSWL=-0.2m	0,65	0,73	0,94	0,88	0,91	0,95
Impact factor ΔSWL=0.5m	0,55	0,73	1,84	0,83	0,90	0,95

WEAK						
Resistance = 1000d	Soil profile C					
	Mid parcel			Edge parcel		
Regional head	High +3	Neutral	Low -2	High +3	Neutral	Low -2
SWL -1m (ref)	-1,233	-1,336	-1,412	-1,083	-1,115	-1,137
SWL -1.2m	-1,367	-1,488	-1,587	-1,261	-1,298	-1,324
SWL -1.5m	-1,540	-1,722	-1,933	-1,516	-1,572	-1,611
▨	▨	▨	▨	▨	▨	▨
Impact factor ΔSWL=-0.2m	0,67	0,76	0,88	0,89	0,92	0,94
Impact factor ΔSWL=0.5m	0,61	0,77	1,04	0,87	0,91	0,95

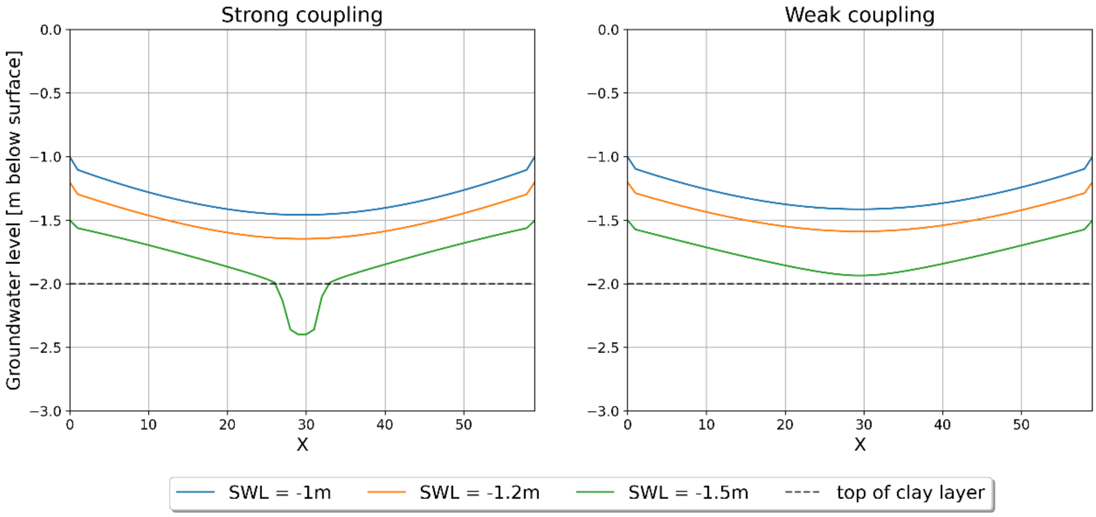


Figure 7-1 GWT across the parcel for base set soil profile C and low regional head (downward seepage) at the moments at which the lowest GWT occurs in the centre of the parcel (used to calculate the impact factors). Profiles are shown for the reference and lowered SWLs. Left: strong coupling. Right: weak coupling.

The explanation for the GWT lowering exceeding the SWL lowering is two-fold.

1. Markedly reduced inflow from the ditches. A key feature of soil profile C is the top high conductivity layer (to the base of the ditches at -2 m). During drought, water from the ditches flows into the parcel via this top layer. For the reference SWL, this inflow is efficient due to the large saturated height over which the inflow occurs at the ditch (1 m). This efficient inflow carries ample water up to the centre of the parcel and this limits the GWT lowering caused by evapotranspiration and downward seepage there (blue curves in Figure 7-1). When SWL is lowered by 0,5 m, the inflow from the ditches is markedly reduced as the saturated thickness at the ditch is halved. For the weak coupling scenario (green curve in right panel of Figure 7-1), the ditch water then barely reaches to the centre of the parcel. The reduced lateral inflow at the centre of the parcel shifts the water balance there towards greater dominance of downward seepage and evapotranspiration, which results in more GWT lowering than for the reference SWL. This shift explains the impact factor > 1.
   For the strong coupling scenario (green curve in left panel of Figure 7-1), where downward seepage is somewhat stronger, the inflowing ditch water for the low SWL is totally ‘used’ by the downward seepage and evapotranspiration before it can reach the parcel centre. The inflow from the ditches is nullified there and further lowering is solely determined by (continued) downward seepage and evapotranspiration[22]. The GWT drops below the base of the conductive layer into the underlying clay. The major change in the local water balance at the centre of the parcel explains to a considerable extent the rather large impact factor >1. The second factor that contributes is explained next.

2. Reduction in phreatic storage when the GWT drops below the sand layer into the underlying clay. Figure 7-2 shows how the phreatic storage coefficient S_y (specific yield) varies with GWT depth for soil profile type C (base set). S_y is the ratio of the water loss between the land surface and the GWT (for instance in mm) and the GWT drop associated with this loss (also in mm). Figure 7-2 shows:
   - When the GWT is near the land surface, a given water loss results in a large GWT drop, because the S_y is small.

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[22] Evapotranspiration becomes progressively less important for deeper GWT.

- The GWT drop for the same water loss decreases for increasing depth of the GWT in the sand layer, because S_y increases.
- The GWT drop for the same water loss increases for increasing depth of the GWT in the underlying clay layer.

The latter implies that once the GWT reaches the top of the clay layer, the rate of GWT decline ‘accelerates’ for the same rate of water loss. Since the rate of water loss in the calculated scenario is dominated by downward seepage, it is virtually constant.

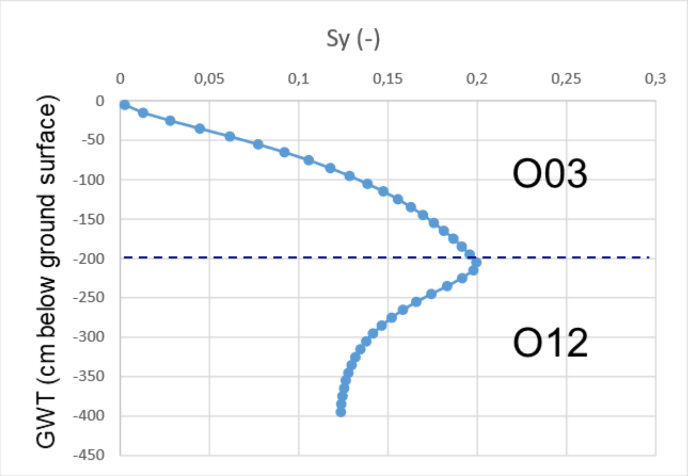

Figure 7-2 Specific yield (= phreatic storage coefficient) as a function of GWT depth below the ground surface for soil profile C (base set). The increasing S_y with depth in the sand (O03) changes to a reduction with depth when the GWT drops into the underlying clay (O12).

7.2 Sensitivity

The calculated variants are meant to clarify to what extent the characteristics of the base set outlined in paragraph 7.1.1, are insensitive to modified conditions and, hence, robust, or sensitive to modified conditions and, hence, more coincidental and less well constrained. Where sensitivity applies, it is of value to discern if the relevant condition affects the impact factor in a systematic way. Apart from the defined variants, potential systematic influences of the regional head, the strength of regional coupling and the magnitude of SWL lowering are of interest.

Figure 7-3 provides a graphical overview of the sensitivities. The figure is an expansion of the figure shown in the 3rd column of Table 7-1 by including of the results for the variants.

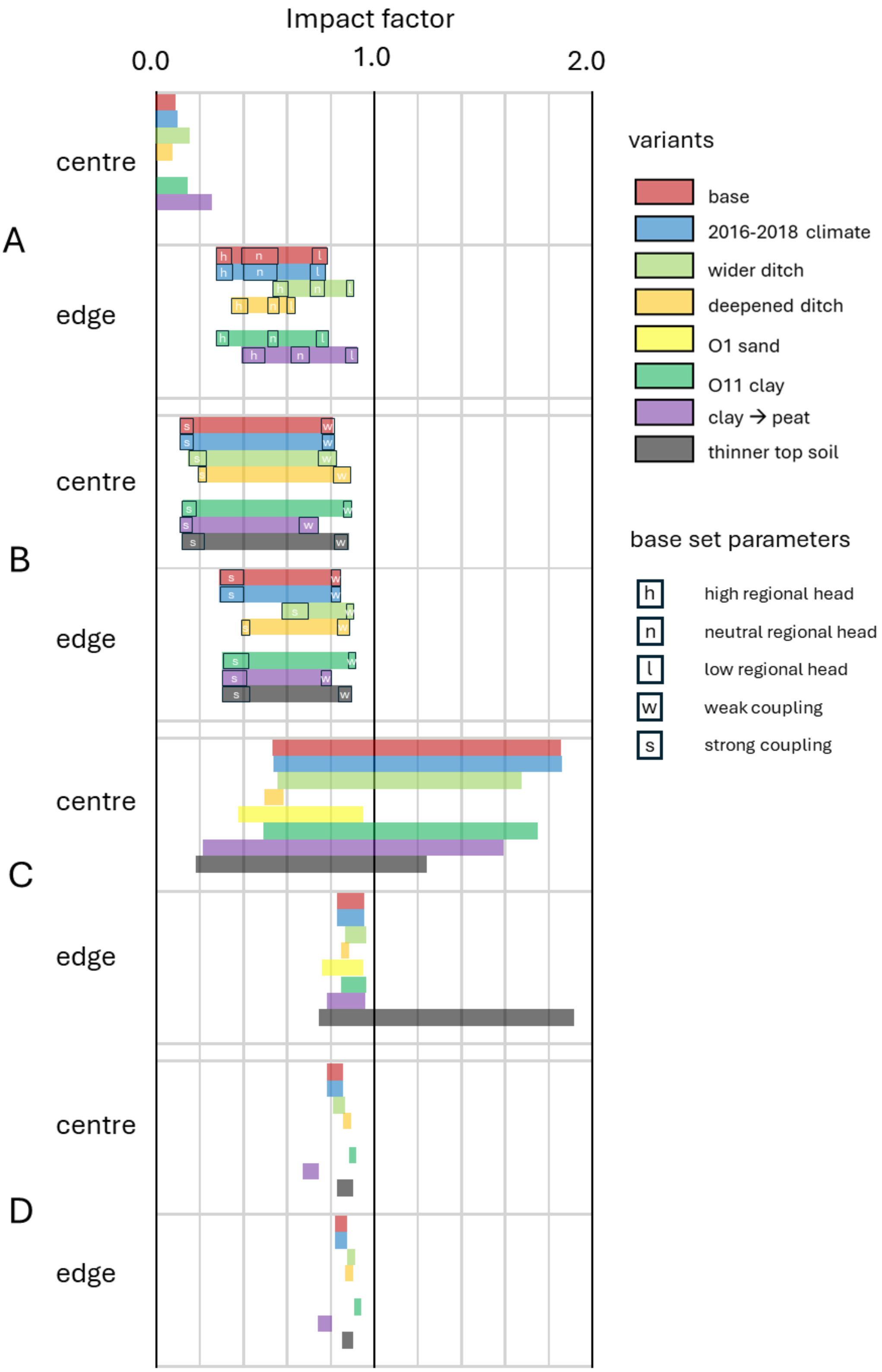

Figure 7-3 Graphical overview of the impact factor range for the base set and the variants thereof, shown as horizontal colour bars. Variants not shown are not applicable/ not calculated. On the left, letters A,B,C,D indicate the soil profile type; 'centre' and 'edge' indicate position in a parcel. Each colour bar range shown is based on 12 simulations: 2 SWL lowering magnitudes and 6 combinations of the 'base set parameters' for regional coupling (legend and Table 2-1). Where a systematic influence of 'base set parameters' is apparent, this is shown through the lettered boxes.

The following insights are gleaned from Figure 7-3 and the results presented in Appendices B, C and D:

1. The impact factor characteristics (colour bar ranges) of soil profile types A, B and in particular D are rather insensitive to the studied variants. Recognition of these profile types, therefore, provides fairly well constrained impact factor ranges for locations close to and distant from the parcel-bounding ditches. For ‘A edge’ and soil profile type B, a systematic influence of the indicated base set parameters is apparent and may be used to narrow the (uncertainty) range.

2. The impact factor characteristics of soil profile type C are very sensitive to several of the variants, as well as to (combinations of) the base set parameters (including the magnitude of SWL lowering not shown in the legend). The impact factor for this soil type has a very large uncertainty range. Uncertainty reduction requires detailed knowledge of many factors.

The sensitivity for profile type C is discussed separately under point 9. First, the role of the individual variants is discussed.

3. *Climate/weather preceding years.* The impact factor is insensitive to the climate/weather conditions in the years preceding a year of drought (2016-2018 variant). Figure 7-4 shows an example illustrating that in the 3rd year of the simulation differences with respect to the base set model (3 x 2018 climate) still exist during the first months. Later in the year, during the drought, the GWT series of the base set model and the variant coincide. Insensitivity of the impact factors to preceding year(s) weather does not imply that the preceding weather conditions also are of no consequence for the lowest GWT in the year of drought. The latter is not the focus of this study and has not been analysed.

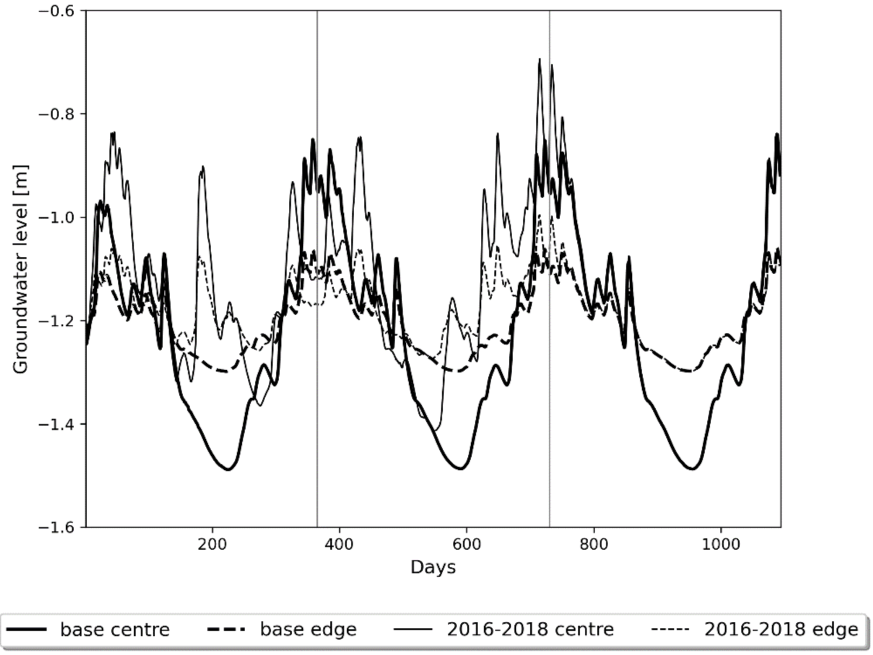

Figure 7-4 Comparison of GWT time series of the base set model (3 x 2018 climate) and 2016-2018 climate variant for the full three years of simulation. The vertical lines separate the individual years. Results shown are for soil type C, SWL=-1.2 m, neutral head and strong coupling.

4. *Parcel bounding water courses.* The sensitivity to ditch width is rather small. A wider ditch can slightly increase the impact factor. The effect is most pronounced at the parcel edge for soil profile types A and B.
   The sensitivity to ditch deepening with SWL lowering similarly is rather small, with the exception of soil profile type C. Ditch deepening can both increase an decrease the impact factor. Increase is observed for soil profile types B and D. This reflects a slightly stronger control of the ditch SWL on the hydraulic head in the sand underneath the clay cover layer when the ditch is deepened. Decrease is found for profile type A. Without ditch deepening SWL lowering reduces the flow from the ditches to the groundwater for the low GWT during the dry period due to the reduction of the wetted height of the ditch wall. With ditch deepening the wetted height is maintained, flow into the parcel during the dry period relatively stronger, resulting in somewhat a higher low GWT (and smaller impact factor).

5. *Clay type*. The sensitivity to clay type is very small. The minor increase of the impact factor for soil profile type D is likely due to the reduced capacity for capillary rise for the clay of the variant (O11; clay mineral content 25%-35%) compared with the clay type of the base set (O12; clay mineral content 35%-50%). Minor differences may result from the different water storage properties of the clays.

6. *Sand type*. Sensitivity to his variable is only investigated/relevant for soil profile type C and is discussed under point 9.

7. *Peat or clay*. The sensitivity to lithology type peat or clay (both associated with low hydraulic conductivity) is moderate and variable. For soil profile type A, peat is associated with slightly larger impact factors. This is likely due to the higher horizontal conductivity than for clay. For soil profile type D, peat is associated with smaller impact factors. This is likely due to greater evapotranspiration reduction in the depth range of the GWT associated with the range of SWL (for SWL = 1 m, the evapotranspiration at the lowest GWT is still relatively high, while for SWL = -1.5 m, the evapotranspiration at the lowest GWT is much reduced). For clay, evapotranspiration is generally low for the employed range of SWL.

8. *Top layer thickness*. The sensitivity to top soil *clay* layer thickness (types B and D) is very small. The sensitivity to top soil *sand* layer thickness (soil profile type C) is large and is discussed under point 9.

9. *Soil profile type C*. In contrast to soil profiles A,B and D, the impact factor of soil profile type C is very sensitive to several variables (Figure 7-3). The tenet of this soil profile type is a high conductivity top layer (sand in the calculations), which supports flow of ditch water into the parcel during drought. As explained in paragraph 7.1.2, this inflow exerts a strong control on the deepest GWT during drought (GWT_{low}). At locations in the parcel where inflow compensates for water loss by evapotranspiration and/or downward seepage – this prevails closer to the ditches – , GWT_{low} will stay in the conductive layer, preventing a deep GWT_{low} to develop. Otherwise, further from the ditches, evapotranspiration and/or downward seepage is left uncompensated. This allows the GWT, and hence GWT_{low}, to drop into the underlying low conductivity soil. A low storage capacity of the low conductivity soil then contributes to development of a very low GWT_{low}. The GWT profile across a parcel for such conditions is characterized by shallow GWT ‘flanks’ and a deep GWT depression in the central parts of a parcel (see for example the green profile in the left panel of Figure 7-1). And if inflow is very efficient, the ‘central depression’ may be absent, the ‘flanks’ extending to the centre of the parcel (the other profiles in Figure 7-1).

SWL lowering alters the GWT$_{low}$ profile for the reference SWL through a reduction of the lateral inflow in the shallow conductive layer. Due to this reduction of inflow, a ‘central depression’ may develop (this was found for the base set model, Figure 7-1). Or an existing central depression may become wider and deeper. The latter is illustrated in Figure 7-5, for the variant with the smaller top layer thickness. High impact factors > 1 are found where ‘flank’ turns into ‘central depression’. Note that this occurs at the edges of a widening ‘central depression’ (this can be anywhere in a parcel). Low(er) impact factors, mostly < 1, are found elsewhere. Note the latter can occur both close to the ditches, when ‘flank’ stays ‘flank’, but also in the centre of a parcel when ‘central depression’ stays ‘central depression’.

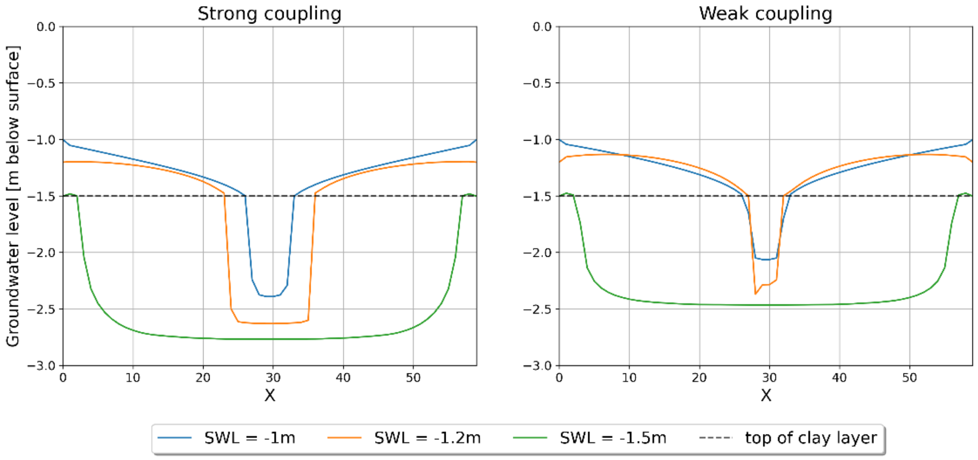

Figure 7-5 GWT across the parcel for the variant with the thinner top soil sand layer at the moments at which the lowest GWT occurs in the centre of the parcel (soil profile C, low regional head (downward seepage)). Profiles are shown for the reference and lowered SWLs. Left: strong coupling. Right: weak coupling. The cross-sections explain the relatively low impact factor(s) at the centre of the parcel, and the high impact factor(s) closer to the edge of the parcel.

These complex relationships largely explain the graphical results of Figure 7-3. Ditch deepening, for instance, results in a very large impact factor decrease in *the centre* of the parcel (from about 1.84 to 0.56) for the SWL lowering by 0.5 m. This reflects a (slightly) higher lateral inflow for the variant with ditch deepening relative to the base model. This relatively enhanced inflow prevents the ‘flank’ to ‘central depression’ change at the centre of the parcel; a change that does occur in the base model. Obviously, the large reduction of the impact factor for ditch deepening is not a general, but highly dependent on other factors. As a second example, the thinner top soil variant results in a large impact factor increase *at the edge* of the parcel compared to the base model (from 0.95 to 1.91). This increase reflects stronger reduction of lateral inflow due to SWL lowing for the thinner top soil than for the base case, causing a ‘flank’ to ‘central depression’ change relatively close to the ditches (Figure 7-5). At *the centre* of the parcel, by contrast, the impact factor for the thinner top soil is markedly reduced compared to the base model (from 1.85 to 0.77). This reflects the fact that while in the base model, a ‘flank’ to ‘central depression’ change occurs, in the model with the reduced thickness top soil sand, the ‘central depression’ is already present for the reference SWL (Figure 7-5).

These examples show that, for soil profile type C, details of the reference situation matter (a lot). Moreover, although sensitivity was investigated by changing single variables, sensitivity clearly is multi-variate. Therefore, apparent sensitivities in Figure 7-3 for soil profile type C can be coincidental. Ditch deepening, for instance, clearly has the potential to, but does not generally prevent impact factors > 1 in the centre of a parcel. The complex dependencies and large sensitivity imply that a large uncertainty bandwidth, roughly between 0.2 and 2.0, should be assigned to the impact factor of this soil profile type. Towards the ditches, the lower bound of the bandwidth becomes higher due to better connectivity of the groundwater and the ditch water. Comprehensive study of local conditions, including the GWT, is required if the bandwidth needs to be refined.

7.3 A new practical table

The aim of the research, formulated in paragraph 1.1.2, is to generate knowledge/information for establishing a practical set of tables of the SWL-lowering impact factors that can be used in the context of building damage (risk) assessment. Graphical tables seem best suited to capture the rather complex relationships documented in this report. Figure 7-6 summarizes the essential findings. This graphical depiction can be used as the practical entry to estimate an applicable impact factor range for a specific area or the site location of an individual building.

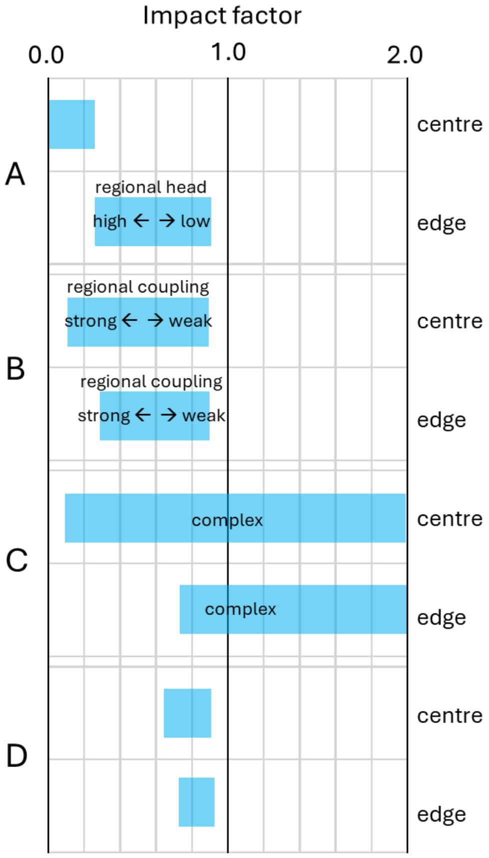

Figure 7-6 Generalized representation of the modelling results showing the estimated impact factor range (blue bars) associated with a soil profile type (A to D) and location in a parcel (edge = a few meters from a ditch; centre = considerably larger distance from ditches). For 'A edge' and 'B', the sensitivity to a key controlling factor within the impact factor range is indicated. For soil profile type 'C', the impact factor controls are many and complex. More sharply defined impact factor estimation for 'C' required detailed, local field information.

7.4 Comparison with the impact factors reported in 1987 by the Commissie Bodemdaling door Aardgaswinning

Over the last decades, the 1987 report of Commissie Bodemdaling door Aardgaswinning (CBA) [3] provided the most comprehensive guidance for estimating GWT lowering caused by SWL lowering. This guidance was provided in the form of (two) tables listing model-calculated (ground)water table lowering for a ditch (water) level lowering by 0.2 m. The table that is most amenable for comparison with the results of the present study is reproduced below[23] (Table 7-3). The impact factor (not part of the original table) is added in the 4th column to facilitate comparison with the results of the present study. Key aspects of the modelling are undocumented and, therefore, unclear, but it is known that the used climatic conditions are those of the dry year 1976. Furthermore, it is stated that the “mean lowest groundwater level” (abbreviated in Dutch as GLG), without further specification, was used to quantify the GWT lowering.

Table 7-3 1987 Guideline. Lowering of the mean lowest groundwater level (in a very dry summer) in the middle of a parcel for a ditch level lowering of 0.20 m. Reproduction of Table 1, p. 28 in the original report [3].

Soil profile predominantly consisting of:	**Ditch level lowering (m)**	**Water table lowering (m)**	**Impact factor**
Clay	0.20	< 0.05	< 0.25
Peat (with clay cover layer)	0.20	0.05-0.10	0.25 – 0.50
Sand	0.20	0.10-0.15	0.50 – 0.75

The CBA classification of impact factors is based on the three ‘soil types’ shown in Table 7-3. The CBA soil type ‘Clay’, in the present study, is covered by soil profile types A, B and D. The inferred impact factors for these profile types for the middle of a parcel are:

Profile type A: 0.00 – 0.15 (slightly higher values in Figure 7-6 apply to peat)
Profile type B: 0.10 – 0.90
Profile type D: 0.65 – 0.90

The CBA results are comparable to the results of profile type A. However, the results for profile types B and D show that clay soils can be associated with much higher impact factors when the clay is relatively thin, and overlies a shallow aquifer that connects with the ditches. Moreover, due to presence of shrinkage cracks and other macropore structures, the top soil of deep clay profiles can be very permeable, in which case such profiles may approximate profile type C, which is associated with impact factors ranging between 0.10 and 2.0. Therefore, also for clay profiles, impact factors > 1 cannot be ruled out.

The CBA soil type ‘Peat’, in the present study, also is covered by soil profile types A, B and D. The inferred impact factors for these profile types for the middle of a parcel are:

Profile type A: 0.00 – 0.25
Profile type B: 0.10 – 0.75
Profile type D: 0.60 – 0.80

And when a permeable peat overlies a clay, profile type C may also apply, indicating that impact factors > 1 cannot be ruled out. This implies that the impact factor may both be considerably smaller than the lower bound 0.25, and considerably higher than the upper bound 0.50 shown in Table 7-3.

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[23] A second table, Table 3, p. 64 in [3] presents results that include the effect of presence of a large building and groundwater lowering in the surroundings and beneath ‘the building’. However, the conditions and impacts that are represented are unclear and largely unsuitable for comparison with results of the present study.

The CBA soil type ‘Sand’, in the present study, is covered by soil profile type C. The inferred impact factor for this soil type are:

Profile type C: 0.10 – 2.0

This shows that the CBA table greatly underestimates the possible impact range.

Overall, the above comparison shows that the CBA table, which uses a classification based on presence of a single dominant soil type clay, sand or peat, does not provide a reliable basis to estimate the SWL lowering impact factor. The impact factor range provided for the individual soil types is too small. This implies that impact factors can both be significantly underestimated and overestimated. Other factors exert a strong and often dominant control on the impact factor and, therefore, need to be considered. These factors include the deeper subsoil permeability structure represented by the four soil profile types (A to D) of the present study, and the coupling with the regional (ground)water system.

8 Inventory of opportunities for validation

The knowledge base, and the established new practical table for estimating impact factors of GWT lowering in response to SWL lowering presented in this report, are purely model based. The modelling approach is essential, as it provides the only means to develop the required generic framework. At the same time, it is desirable to put the modelling and the findings to the test.

Usable existing observational datasets of the GWT response to SWL lowering to conduct such testing are not known to exist. Therefore, in task V2, water boards were asked for upcoming SWL adjustment plans in the next few years, with the aim to inventory opportunities for dedicated long-term monitoring and testing/validation in potential follow-up research. All twenty-one water boards in the Netherlands were contacted (by email). In the request, the water boards were asked about their plans to implement a significant (at least 10 cm), permanent, or long lasting, SWL lowering in their management area. The purpose of the request was explained to the water boards, also pointing out ample time required for arrangement and pre-SWL lowering monitoring.

Seventeen waterboards replied to the request.
Most responses indicate directly or indirectly that no such plans/opportunities exist:

- Several water boards, especially those in areas with (low lying) soft soils, mentioned they use periodic (every couple of years) water level indexation to compensate for land subsidence (reduction of freeboard). However, this SWL lowering is generally on the order of a few centimetres and occurs stepwise over the years.
- Water board Brabantse Delta reported plans for a shift of the boundary of a constant water level area (shift of a weir) that results in a very localized (parcel scale) SWL change. Because of the small spatial scale, such plans do not provide opportunities for the envisaged testing, as the GWT response would be strongly influenced by the nearly unadjusted SWLs.
- Water board Hoogheemraadschap van Rijnland reported plans for substantial SWL raising at new housing projects (e.g., Valkenhorst: +0.39 m (summer SWL); Dever-Zuid, Lisse: +0.61 m (summer SWL)). Although the response to SWL raising might also provide useful constraints, the setting in which the SWL raising occurs in these instances is unsuitable for the envisaged testing/validation due to many other modifications in the hydrological situation.

One response presents a potential opportunity:

- Water board Noorderzijlvest shared plans to raise SWLs in “Het Zuidelijk Westerkwartier” near Marum in the province of Groningen [18]. The SWL raise varies spatially, but includes extensive areas where the SWL will be raised between 0.05-0.25 m and between 0.25 – 1.00 m. In certain places, this entails a raise of more than 0.8 m. The SWL changes are planned for December 2026, leaving time to further explore its potential for monitoring and testing and for establish a monitoring plan.

9 Conclusions and recommendations

9.1 Conclusions

The following issues and challenges of this KEM16b project (derived from the preceding KEM16 project and interim report [1]) have been addressed and met:

1. Presumed problems with improperly calculated (interim) models have been clarified and resolved (task P1).
    - The water balances of the models of the interim report [1] contained unacceptably large water-balance errors (up to 153.9% for soil profile A). This could be (and was) remedied by tightening the convergence criteria.
    - The unrealistic spiked GWT response to precipitation events in the interim models was found to be a deficiency of MODFLOW6. MODFLOW6 calculates a spurious hydraulic head field (and ambiguous GWT) for the following combination of conditions: (a) the imposed recharge exceeds the vertical (saturated) hydraulic conductivity above the GWT, (b) the soil above the GWT contains a finely discretised stack of model cells. This combination occurs in several of the interim models. The issue was resolved by switching to a MetaSWAP-MODFLOW6 code, where MetaSWAP handles unsaturated zone conditions and water transfer.

2. Feedback and support has been obtained on/for the general approach (task P2).
    - One Deltares expert and two external experts reviewed the interim report [1]. The experts judged the general approach “defensible”, “yields useful insights” and “workable/practicable”. The experts also confirmed the concerns/considerations and needs for improvement that were raised in the interim report [1]:
        - ✓ The need for improved unsaturated zone processes representation.
        - ✓ The unrealistic nature of the peaks in the GWT response to precipitation events.
        - ✓ The need for more extensive sensitivity analysis.
    - Guided by specific comments, the parametrization of the high and low regional head in the models was modified to prevent unrealistic, excessive magnitudes of upward and downward seepage in the model set.

3. The representation and controls of unsaturated zone water transfer and storage are improved in the modelling (tasks M1 and M2).
    - These improvements were achieved though usage of the MetaSWAP-MODFLOW6 code, where MetaSWAP handles the unsaturated zone.
    - To allow use of MetaSWAP for the current project, the coupling with MODFLOW6 was recoded to ensure that MetaSWAP couples with the GWT-containing cell, both in model time steps and in the iterative scheme.

4. A historical GWT time series has been modelled, providing a basic validation of the modelling approach with MetaSWAP-MODFLOW6 and the adopted parametrization systematics (task V1).
    - The modelling reproduces the key characteristics of a GWT-time series in a thick clayey profile in the north of the province of Groningen (near Termunten).

5. A comprehensive dataset of impact factors[24] has been generated. Besides the base model set – this corresponds to the model set developed in the interim report (KEM16) –

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[24] The ratio of the lowering of the lowest GWT and the lowering of the SWL.

variants thereof were used to quantify the sensitivity of the impact factors to various parameters and conditions (task M3). This dataset of impact factors, the underlying GWT time series, and the understanding thereof, represents the (improved) knowledge base of the chain link between SWL lowering and GWT lowering.

6. A graphical table (Figure 7-6) has been developed as a practical entry for estimating the impact factor (range) for a specific area or the site location of an individual building.
    - The table provides impact factor ranges for the four soil profile types (A,B,C and D), a location a few meters from a parcel-bounding ditch (at the ‘edge’), and for locations substantially further from the ditches (at the parcel ‘centre’). For some of these ranges, information about the coupling with the regional (ground)water system can be used to reduce the (uncertainty) range.
    - The impact factor for soil profile type C has a very large (uncertainty) range (0.1 – 2.0). The impact factor is not bounded by a maximum value of 1: GWT lowering can exceed SWL lowering. Due to the complex sensitivities, uncertainty reduction requires detailed knowledge of many factors.

7. The 1987 guidelines (Commissie Bodemdaling door Aardgaswinning [3]), which use a classification in terms of a single dominant soil type clay, sand or peat, provide impact factor ranges that are too small: impact factors can both be significantly underestimated and overestimated. Other factors than merely clay, sand or peat exert a strong and often dominant control on the impact factor and, therefore, need to be considered. These factors include the deeper subsoil permeability structure represented by the four soil profile types (A to D) of the present study, and the coupling with the regional (ground)water system.

8. Inventory of SWL adjustment plans with the water boards of The Netherlands has yielded one potential opportunity for a validation study near Marum, Groningen.

9.2 Recommendations

The following recommendations are made:

1. It is recommended to develop a series of example problems to clarify the use of the new tool. These examples should clarify what information can be used, and how the information can be used to judge (a) the applicable soil profile type, and (b) the applicable regional (ground)water coupling conditions that are distinguished in the employed classification system. It is recommended to incorporate the example problems a ‘user guide’. The user guide should also clarify the scope/limitations of the new impact factor table.

2. It is recommended to further clarify the potential of the SWL adjustment plans by water board Noorderzijlvest near Marum, Groningen, late 2026, for development of a validation study. And if positive, to carry out the study.

3. It is recommended to conduct field research into the occurrence of conditions that (according to the modelling) can result in impact factors > 1 (soil profile type C). This can be done by studying the mean deepest GWT (GLG) for sites with this type of soil profile, between ditch and the middle of the parcel, using hydromorphic features derived from vertical coring.

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Appendix A Mining-induced land subsidence and surface water level lowering

Kooi et al (2021; 2023) distinguish two ways in which mining-induced (deep) land subsidence can induce SWL lowering relative to the land surface (in Dutch: increase of freeboard):

(1) By differential subsidence within fixed water level areas. This form of SWL lowering occurs gradually and without active interference in the water system. This is depicted in Figure 9-1. Freeboard increase (red) equals SWL lowering relative to the land surface.

(2) By active SWL lowering by water boards aimed to mitigate effects of 1. Note that when this lowing corrects for a prior SWL rise (freeboard decrease) due to 1, no net SWL lowering may be involved since the start of the deep subsidence.

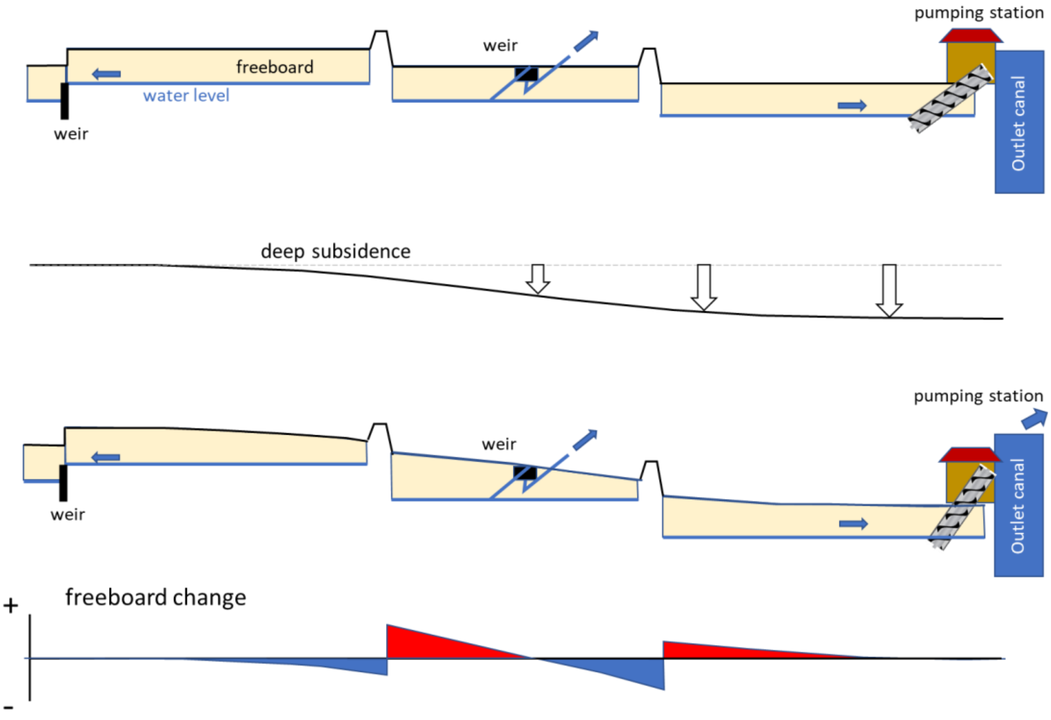
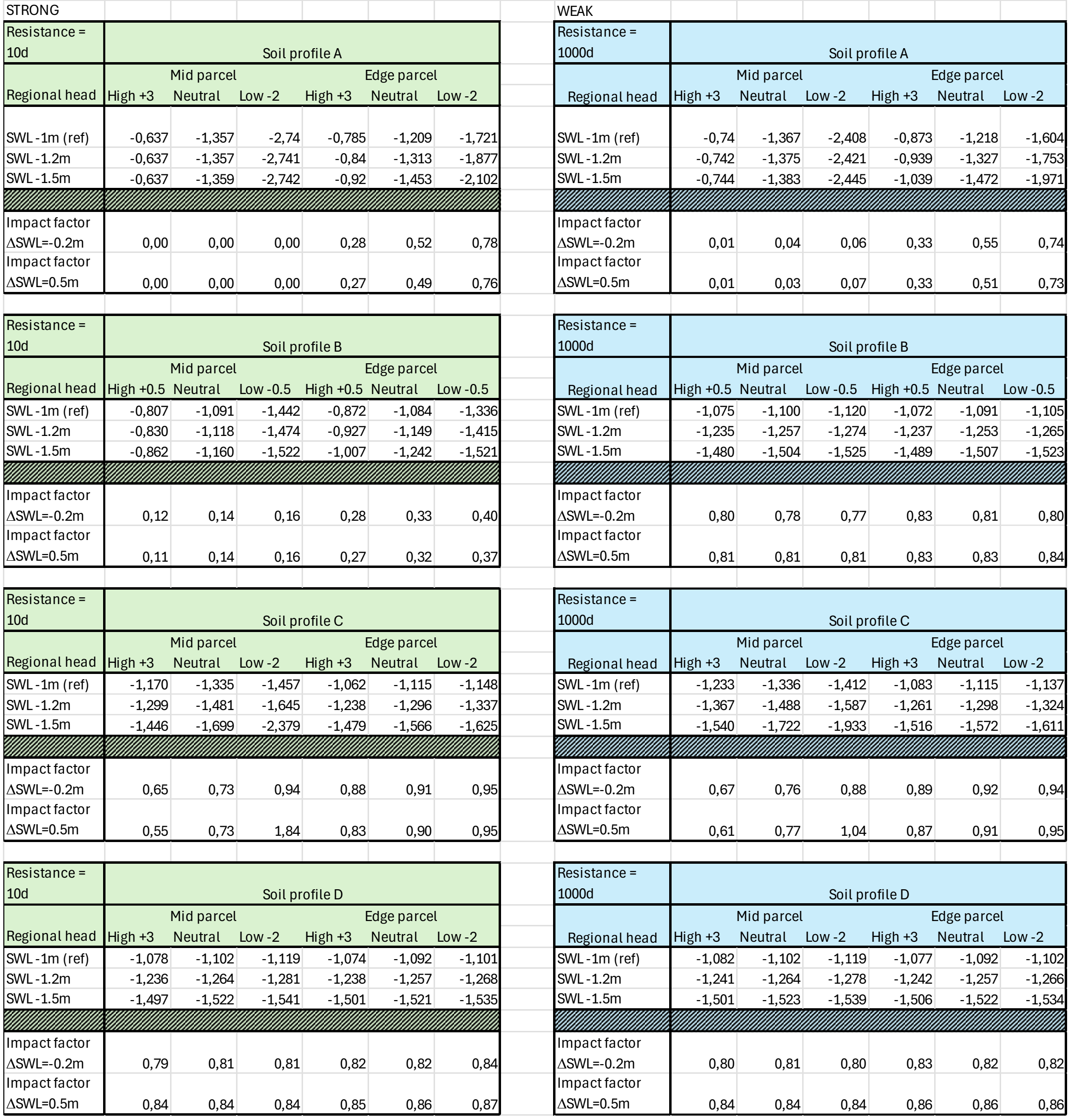


Figure 9-1 Schematic illustration of the effect of deep subsidence on freeboard in the absence of active interference and in the absence of shallow subsidence. Top panel: situation before deep subsidence, showing three fixed water level areas, each with a water level controlling infrastructure (weir or pumping station). At the middle area, the discharge at the weir occurs at the middle of the profile in an out-of-profile direction. The other panels respectively show the deep subsidence, the impact on land level, water level and freeboard, and the freeboard change (red = increase of freeboard, blue = decrease of freeboard). In the sketch is it assumed that the water level at the drainage outlet canal to the right is unaffected by the subsidence or maintained at the original level.

Appendix B Results – tabulated lowest GWT and impact factors

This appendix lists the lowest groundwater level in the third year (2018) for each simulation and the impact factors for the SWL lowering of 0.2 m and 0.5 m. The tables on the left (green) are for strong regional coupling; the tables on the right (blue) for weak regional coupling. Results for the base set and the variants are presented on separate pages. The GWT time series are presented in appendices C1 to C8.

B.1 Base set



STRONG

Resistance = 10d	Soil profile A					
	Mid parcel			Edge parcel		
Regional head	High +3	Neutral	Low -2	High +3	Neutral	Low -2
SWL -1m (ref)	-0,637	-1,357	-2,74	-0,785	-1,209	-1,721
SWL -1.2m	-0,637	-1,357	-2,741	-0,84	-1,313	-1,877
SWL -1.5m	-0,637	-1,359	-2,742	-0,92	-1,453	-2,102
Impact factor ΔSWL=-0.2m	0,00	0,00	0,00	0,28	0,52	0,78
Impact factor ΔSWL=0.5m	0,00	0,00	0,00	0,27	0,49	0,76

Resistance = 10d	Soil profile B					
	Mid parcel			Edge parcel		
Regional head	High +0.5	Neutral	Low -0.5	High +0.5	Neutral	Low -0.5
SWL -1m (ref)	-0,807	-1,091	-1,442	-0,872	-1,084	-1,336
SWL -1.2m	-0,830	-1,118	-1,474	-0,927	-1,149	-1,415
SWL -1.5m	-0,862	-1,160	-1,522	-1,007	-1,242	-1,521
Impact factor ΔSWL=-0.2m	0,12	0,14	0,16	0,28	0,33	0,40
Impact factor ΔSWL=0.5m	0,11	0,14	0,16	0,27	0,32	0,37

Resistance = 10d	Soil profile C					
	Mid parcel			Edge parcel		
Regional head	High +3	Neutral	Low -2	High +3	Neutral	Low -2
SWL -1m (ref)	-1,170	-1,335	-1,457	-1,062	-1,115	-1,148
SWL -1.2m	-1,299	-1,481	-1,645	-1,238	-1,296	-1,337
SWL -1.5m	-1,446	-1,699	-2,379	-1,479	-1,566	-1,625
Impact factor ΔSWL=-0.2m	0,65	0,73	0,94	0,88	0,91	0,95
Impact factor ΔSWL=0.5m	0,55	0,73	1,84	0,83	0,90	0,95

Resistance = 10d	Soil profile D					
	Mid parcel			Edge parcel		
Regional head	High +3	Neutral	Low -2	High +3	Neutral	Low -2
SWL -1m (ref)	-1,078	-1,102	-1,119	-1,074	-1,092	-1,101
SWL -1.2m	-1,236	-1,264	-1,281	-1,238	-1,257	-1,268
SWL -1.5m	-1,497	-1,522	-1,541	-1,501	-1,521	-1,535
Impact factor ΔSWL=-0.2m	0,79	0,81	0,81	0,82	0,82	0,84
Impact factor ΔSWL=0.5m	0,84	0,84	0,84	0,85	0,86	0,87

WEAK

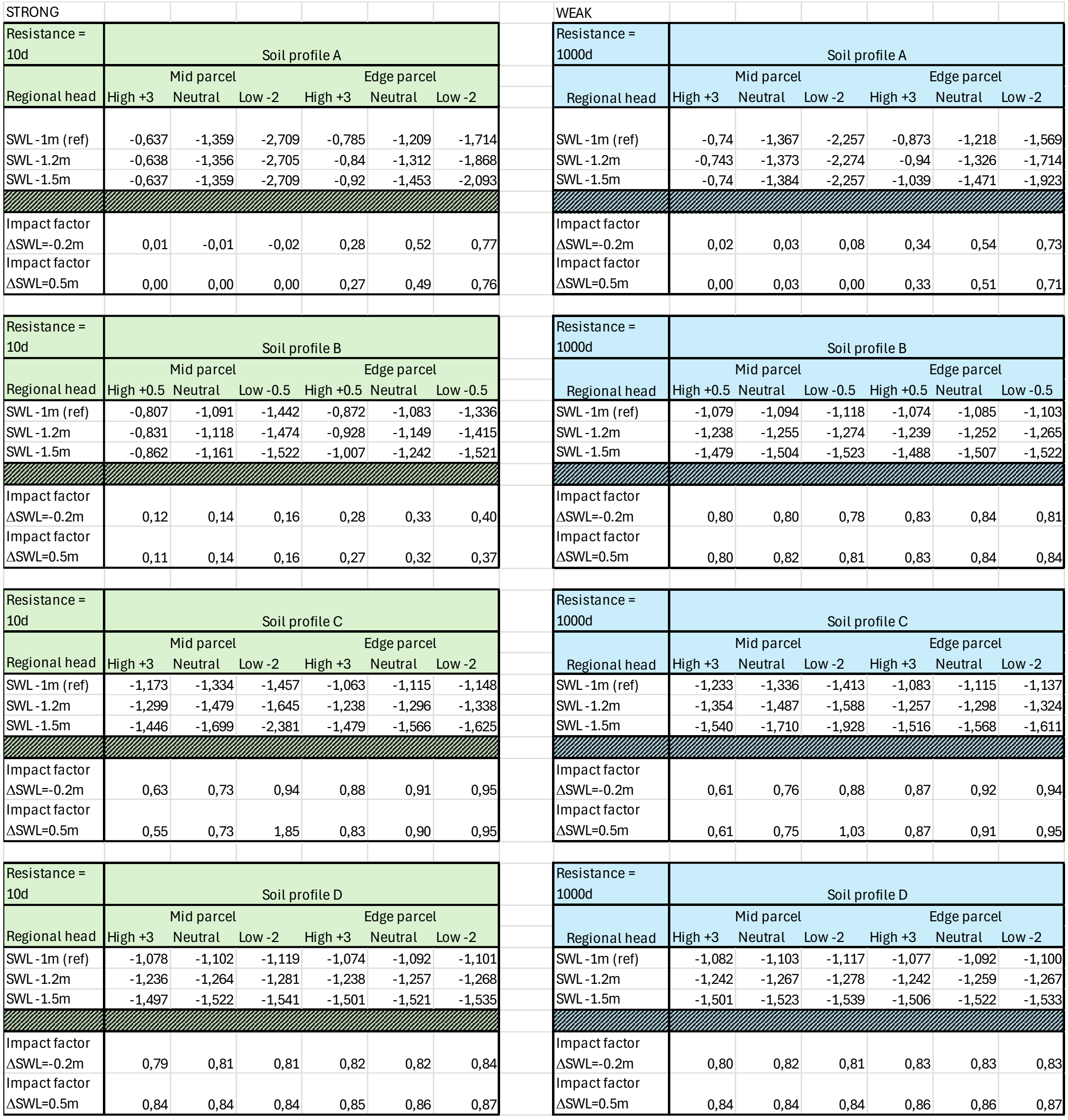
Resistance = 1000d	Soil profile A					
	Mid parcel			Edge parcel		
Regional head	High +3	Neutral	Low -2	High +3	Neutral	Low -2
SWL -1m (ref)	-0,74	-1,367	-2,408	-0,873	-1,218	-1,604
SWL -1.2m	-0,742	-1,375	-2,421	-0,939	-1,327	-1,753
SWL -1.5m	-0,744	-1,383	-2,445	-1,039	-1,472	-1,971
Impact factor ΔSWL=-0.2m	0,01	0,04	0,06	0,33	0,55	0,74
Impact factor ΔSWL=0.5m	0,01	0,03	0,07	0,33	0,51	0,73

Resistance = 1000d	Soil profile B					
	Mid parcel			Edge parcel		
Regional head	High +0.5	Neutral	Low -0.5	High +0.5	Neutral	Low -0.5
SWL -1m (ref)	-1,075	-1,100	-1,120	-1,072	-1,091	-1,105
SWL -1.2m	-1,235	-1,257	-1,274	-1,237	-1,253	-1,265
SWL -1.5m	-1,480	-1,504	-1,525	-1,489	-1,507	-1,523
Impact factor ΔSWL=-0.2m	0,80	0,78	0,77	0,83	0,81	0,80
Impact factor ΔSWL=0.5m	0,81	0,81	0,81	0,83	0,83	0,84

Resistance = 1000d	Soil profile C					
	Mid parcel			Edge parcel		
Regional head	High +3	Neutral	Low -2	High +3	Neutral	Low -2
SWL -1m (ref)	-1,233	-1,336	-1,412	-1,083	-1,115	-1,137
SWL -1.2m	-1,367	-1,488	-1,587	-1,261	-1,298	-1,324
SWL -1.5m	-1,540	-1,722	-1,933	-1,516	-1,572	-1,611
Impact factor ΔSWL=-0.2m	0,67	0,76	0,88	0,89	0,92	0,94
Impact factor ΔSWL=0.5m	0,61	0,77	1,04	0,87	0,91	0,95

Resistance = 1000d	Soil profile D					
	Mid parcel			Edge parcel		
Regional head	High +3	Neutral	Low -2	High +3	Neutral	Low -2
SWL -1m (ref)	-1,082	-1,102	-1,119	-1,077	-1,092	-1,102
SWL -1.2m	-1,241	-1,264	-1,278	-1,242	-1,257	-1,266
SWL -1.5m	-1,501	-1,523	-1,539	-1,506	-1,522	-1,534
Impact factor ΔSWL=-0.2m	0,80	0,81	0,80	0,83	0,82	0,82
Impact factor ΔSWL=0.5m	0,84	0,84	0,84	0,86	0,86	0,86

B.2 2016-2018 climate



STRONG

Resistance = 10d	Soil profile A					
	Mid parcel			Edge parcel		
Regional head	High +3	Neutral	Low -2	High +3	Neutral	Low -2
SWL -1m (ref)	-0,637	-1,359	-2,709	-0,785	-1,209	-1,714
SWL -1.2m	-0,638	-1,356	-2,705	-0,84	-1,312	-1,868
SWL -1.5m	-0,637	-1,359	-2,709	-0,92	-1,453	-2,093
Impact factor ΔSWL=-0.2m	0,01	-0,01	-0,02	0,28	0,52	0,77
Impact factor ΔSWL=0.5m	0,00	0,00	0,00	0,27	0,49	0,76

Resistance = 10d	Soil profile B					
	Mid parcel			Edge parcel		
Regional head	High +0.5	Neutral	Low -0.5	High +0.5	Neutral	Low -0.5
SWL -1m (ref)	-0,807	-1,091	-1,442	-0,872	-1,083	-1,336
SWL -1.2m	-0,831	-1,118	-1,474	-0,928	-1,149	-1,415
SWL -1.5m	-0,862	-1,161	-1,522	-1,007	-1,242	-1,521
Impact factor ΔSWL=-0.2m	0,12	0,14	0,16	0,28	0,33	0,40
Impact factor ΔSWL=0.5m	0,11	0,14	0,16	0,27	0,32	0,37

Resistance = 10d	Soil profile C					
	Mid parcel			Edge parcel		
Regional head	High +3	Neutral	Low -2	High +3	Neutral	Low -2
SWL -1m (ref)	-1,173	-1,334	-1,457	-1,063	-1,115	-1,148
SWL -1.2m	-1,299	-1,479	-1,645	-1,238	-1,296	-1,338
SWL -1.5m	-1,446	-1,699	-2,381	-1,479	-1,566	-1,625
Impact factor ΔSWL=-0.2m	0,63	0,73	0,94	0,88	0,91	0,95
Impact factor ΔSWL=0.5m	0,55	0,73	1,85	0,83	0,90	0,95

Resistance = 10d	Soil profile D					
	Mid parcel			Edge parcel		
Regional head	High +3	Neutral	Low -2	High +3	Neutral	Low -2
SWL -1m (ref)	-1,078	-1,102	-1,119	-1,074	-1,092	-1,101
SWL -1.2m	-1,236	-1,264	-1,281	-1,238	-1,257	-1,268
SWL -1.5m	-1,497	-1,522	-1,541	-1,501	-1,521	-1,535
Impact factor ΔSWL=-0.2m	0,79	0,81	0,81	0,82	0,82	0,84
Impact factor ΔSWL=0.5m	0,84	0,84	0,84	0,85	0,86	0,87

WEAK

Resistance = 1000d	Soil profile A					
	Mid parcel			Edge parcel		
Regional head	High +3	Neutral	Low -2	High +3	Neutral	Low -2
SWL -1m (ref)	-0,74	-1,367	-2,257	-0,873	-1,218	-1,569
SWL -1.2m	-0,743	-1,373	-2,274	-0,94	-1,326	-1,714
SWL -1.5m	-0,74	-1,384	-2,257	-1,039	-1,471	-1,923
Impact factor ΔSWL=-0.2m	0,02	0,03	0,08	0,34	0,54	0,73
Impact factor ΔSWL=0.5m	0,00	0,03	0,00	0,33	0,51	0,71

Resistance = 1000d	Soil profile B					
	Mid parcel			Edge parcel		
Regional head	High +0.5	Neutral	Low -0.5	High +0.5	Neutral	Low -0.5
SWL -1m (ref)	-1,079	-1,094	-1,118	-1,074	-1,085	-1,103
SWL -1.2m	-1,238	-1,255	-1,274	-1,239	-1,252	-1,265
SWL -1.5m	-1,479	-1,504	-1,523	-1,488	-1,507	-1,522
Impact factor ΔSWL=-0.2m	0,80	0,80	0,78	0,83	0,84	0,81
Impact factor ΔSWL=0.5m	0,80	0,82	0,81	0,83	0,84	0,84

Resistance = 1000d	Soil profile C					
	Mid parcel			Edge parcel		
Regional head	High +3	Neutral	Low -2	High +3	Neutral	Low -2
SWL -1m (ref)	-1,233	-1,336	-1,413	-1,083	-1,115	-1,137
SWL -1.2m	-1,354	-1,487	-1,588	-1,257	-1,298	-1,324
SWL -1.5m	-1,540	-1,710	-1,928	-1,516	-1,568	-1,611
Impact factor ΔSWL=-0.2m	0,61	0,76	0,88	0,87	0,92	0,94
Impact factor ΔSWL=0.5m	0,61	0,75	1,03	0,87	0,91	0,95

Resistance = 1000d	Soil profile D					
	Mid parcel			Edge parcel		
Regional head	High +3	Neutral	Low -2	High +3	Neutral	Low -2
SWL -1m (ref)	-1,082	-1,103	-1,117	-1,077	-1,092	-1,100
SWL -1.2m	-1,242	-1,267	-1,278	-1,242	-1,259	-1,267
SWL -1.5m	-1,501	-1,523	-1,539	-1,506	-1,522	-1,533
Impact factor ΔSWL=-0.2m	0,80	0,82	0,81	0,83	0,83	0,83
Impact factor ΔSWL=0.5m	0,84	0,84	0,84	0,86	0,86	0,87

B.3 Wider ditch

STRONG

Resistance = 10d	Soil profile A					
	Mid parcel			Edge parcel		
Regional head	High +3	Neutral	Low -2	High +3	Neutral	Low -2
SWL -1m (ref)	-0,638	-1,358	-2,738	-0,881	-1,121	-1,38
SWL -1.2m	-0,638	-1,358	-2,739	-0,992	-1,268	-1,56
SWL -1.5m	-0,638	-1,359	-2,741	-1,155	-1,477	-1,828
Impact factor ΔSWL=-0.2m	0,00	0,00	0,00	0,56	0,74	0,90
Impact factor ΔSWL=0.5m	0,00	0,00	0,01	0,55	0,71	0,90

Resistance = 10d	Soil profile B					
	Mid parcel			Edge parcel		
Regional head	High +0.5	Neutral	Low -0.5	High +0.5	Neutral	Low -0.5
SWL -1m (ref)	-0,831	-1,091	-1,406	-0,944	-1,055	-1,183
SWL -1.2m	-0,861	-1,131	-1,452	-1,059	-1,180	-1,320
SWL -1.5m	-0,908	-1,193	-1,522	-1,231	-1,364	-1,515
Impact factor ΔSWL=-0.2m	0,15	0,20	0,23	0,58	0,63	0,69
Impact factor ΔSWL=0.5m	0,15	0,20	0,23	0,57	0,62	0,66

Resistance = 10d	Soil profile C					
	Mid parcel			Edge parcel		
Regional head	High +3	Neutral	Low -2	High +3	Neutral	Low -2
SWL -1m (ref)	-1,165	-1,321	-1,436	-1,053	-1,097	-1,125
SWL -1.2m	-1,296	-1,469	-1,623	-1,233	-1,281	-1,315
SWL -1.5m	-1,449	-1,692	-2,264	-1,482	-1,556	-1,605
Impact factor ΔSWL=-0.2m	0,66	0,74	0,94	0,90	0,92	0,95
Impact factor ΔSWL=0.5m	0,57	0,74	1,66	0,86	0,92	0,96

Resistance = 10d	Soil profile D					
	Mid parcel			Edge parcel		
Regional head	High +3	Neutral	Low -2	High +3	Neutral	Low -2
SWL -1m (ref)	-1,081	-1,098	-1,108	-1,051	-1,057	-1,063
SWL -1.2m	-1,242	-1,259	-1,272	-1,230	-1,236	-1,240
SWL -1.5m	-1,503	-1,522	-1,535	-1,507	-1,515	-1,520
Impact factor ΔSWL=-0.2m	0,81	0,80	0,82	0,90	0,90	0,89
Impact factor ΔSWL=0.5m	0,84	0,85	0,85	0,91	0,92	0,91

WEAK

Resistance = 1000d	Soil profile A					
	Mid parcel			Edge parcel		
Regional head	High +3	Neutral	Low -2	High +3	Neutral	Low -2
SWL -1m (ref)	-0,743	-1,369	-2,381	-0,936	-1,126	-1,319
SWL -1.2m	-0,744	-1,375	-2,413	-1,056	-1,275	-1,497
SWL -1.5m	-0,748	-1,387	-2,434	-1,234	-1,489	-1,757
Impact factor ΔSWL=-0.2m	0,01	0,03	0,16	0,60	0,75	0,89
Impact factor ΔSWL=0.5m	0,01	0,04	0,11	0,60	0,73	0,88

Resistance = 1000d	Soil profile B					
	Mid parcel			Edge parcel		
Regional head	High +0.5	Neutral	Low -0.5	High +0.5	Neutral	Low -0.5
SWL -1m (ref)	-1,081	-1,093	-1,106	-1,051	-1,056	-1,063
SWL -1.2m	-1,240	-1,257	-1,266	-1,228	-1,236	-1,239
SWL -1.5m	-1,450	-1,509	-1,523	-1,503	-1,509	-1,515
Impact factor ΔSWL=-0.2m	0,80	0,82	0,80	0,89	0,90	0,88
Impact factor ΔSWL=0.5m	0,74	0,83	0,83	0,90	0,91	0,90

Resistance = 1000d	Soil profile C					
	Mid parcel			Edge parcel		
Regional head	High +3	Neutral	Low -2	High +3	Neutral	Low -2
SWL -1m (ref)	-1,222	-1,323	-1,399	-1,070	-1,098	-1,117
SWL -1.2m	-1,361	-1,475	-1,568	-1,252	-1,283	-1,304
SWL -1.5m	-1,537	-1,713	-1,905	-1,513	-1,561	-1,594
Impact factor ΔSWL=-0.2m	0,70	0,76	0,85	0,91	0,92	0,94
Impact factor ΔSWL=0.5m	0,63	0,78	1,01	0,89	0,93	0,95

Resistance = 1000d	Soil profile D					
	Mid parcel			Edge parcel		
Regional head	High +3	Neutral	Low -2	High +3	Neutral	Low -2
SWL -1m (ref)	-1,084	-1,098	-1,106	-1,052	-1,057	-1,062
SWL -1.2m	-1,246	-1,259	-1,270	-1,231	-1,236	-1,240
SWL -1.5m	-1,507	-1,523	-1,534	-1,508	-1,515	-1,519
Impact factor ΔSWL=-0.2m	0,81	0,80	0,82	0,90	0,90	0,89
Impact factor ΔSWL=0.5m	0,85	0,85	0,86	0,91	0,92	0,91

B.4 Ditch deepend with SWL lowering

STRONG

Resistance = 10d	Soil profile A					
	Mid parcel			Edge parcel		
Regional head	High +3	Neutral	Low -2	High +3	Neutral	Low -2
SWL -1m (ref)	-0,637	-1,357	-2,743	-0,785	-1,209	-1,725
SWL -1.2m	-0,637	-1,359	-2,74	-0,853	-1,312	-1,846
SWL -1.5m	-0,637	-1,36	-2,74	-0,964	-1,466	-2,03
Impact factor ΔSWL=-0.2m	0,00	0,01	-0,01	0,34	0,52	0,61
Impact factor ΔSWL=0.5m	0,00	0,01	-0,01	0,36	0,51	0,61

Resistance = 10d	Soil profile B					
	Mid parcel			Edge parcel		
Regional head	High +0.5	Neutral	Low -0.5	High +0.5	Neutral	Low -0.5
SWL -1m (ref)	-0,807	-1,091	-1,442	-0,872	-1,084	-1,336
SWL -1.2m	-0,850	-1,133	-1,482	-0,951	-1,162	-1,417
SWL -1.5m	-0,904	-1,194	-1,542	-1,074	-1,287	-1,538
Impact factor ΔSWL=-0.2m	0,22	0,21	0,20	0,40	0,39	0,41
Impact factor ΔSWL=0.5m	0,19	0,21	0,20	0,40	0,41	0,40

Resistance = 10d	Soil profile C					
	Mid parcel			Edge parcel		
Regional head	High +3	Neutral	Low -2	High +3	Neutral	Low -2
SWL -1m (ref)	-1,171	-1,332	-1,457	-1,062	-1,114	-1,148
SWL -1.2m	-1,285	-1,434	-1,557	-1,232	-1,283	-1,320
SWL -1.5m	-1,455	-1,616	-1,736	-1,483	-1,542	-1,580
Impact factor ΔSWL=-0.2m	0,57	0,51	0,50	0,85	0,84	0,86
Impact factor ΔSWL=0.5m	0,57	0,57	0,56	0,84	0,86	0,86

Resistance = 10d	Soil profile D					
	Mid parcel			Edge parcel		
Regional head	High +3	Neutral	Low -2	High +3	Neutral	Low -2
SWL -1m (ref)	-1,078	-1,102	-1,119	-1,074	-1,092	-1,101
SWL -1.2m	-1,250	-1,274	-1,292	-1,249	-1,265	-1,277
SWL -1.5m	-1,514	-1,541	-1,562	-1,519	-1,538	-1,551
Impact factor ΔSWL=-0.2m	0,86	0,86	0,87	0,88	0,86	0,88
Impact factor ΔSWL=0.5m	0,87	0,88	0,89	0,89	0,89	0,90

WEAK

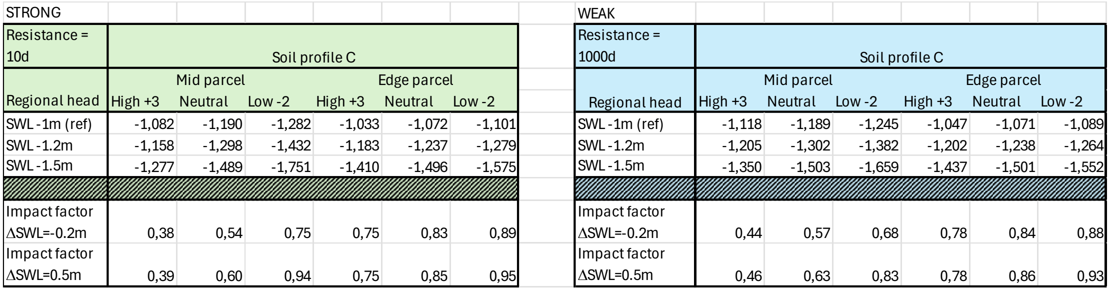
Resistance = 1000d	Soil profile A					
	Mid parcel			Edge parcel		
Regional head	High +3	Neutral	Low -2	High +3	Neutral	Low -2
SWL -1m (ref)	-0,74	-1,367	-2,408	-0,873	-1,218	-1,604
SWL -1.2m	-0,742	-1,372	-2,42	-0,953	-1,326	-1,728
SWL -1.5m	-0,748	-1,385	-2,44	-1,082	-1,484	-1,918
Impact factor ΔSWL=-0.2m	0,01	0,03	0,06	0,40	0,54	0,62
Impact factor ΔSWL=0.5m	0,02	0,04	0,06	0,42	0,53	0,63

Resistance = 1000d	Soil profile B					
	Mid parcel			Edge parcel		
Regional head	High +0.5	Neutral	Low -0.5	High +0.5	Neutral	Low -0.5
SWL -1m (ref)	-1,075	-1,100	-1,120	-1,072	-1,091	-1,105
SWL -1.2m	-1,250	-1,267	-1,282	-1,248	-1,261	-1,271
SWL -1.5m	-1,503	-1,523	-1,545	-1,510	-1,524	-1,540
Impact factor ΔSWL=-0.2m	0,88	0,83	0,81	0,88	0,85	0,83
Impact factor ΔSWL=0.5m	0,86	0,85	0,85	0,88	0,87	0,87

Resistance = 1000d	Soil profile C					
	Mid parcel			Edge parcel		
Regional head	High +3	Neutral	Low -2	High +3	Neutral	Low -2
SWL -1m (ref)	-1,237	-1,334	-1,411	-1,083	-1,115	-1,136
SWL -1.2m	-1,342	-1,431	-1,512	-1,253	-1,281	-1,307
SWL -1.5m	-1,515	-1,625	-1,702	-1,505	-1,545	-1,570
Impact factor ΔSWL=-0.2m	0,53	0,49	0,51	0,85	0,83	0,86
Impact factor ΔSWL=0.5m	0,56	0,58	0,58	0,84	0,86	0,87

Resistance = 1000d	Soil profile D					
	Mid parcel			Edge parcel		
Regional head	High +3	Neutral	Low -2	High +3	Neutral	Low -2
SWL -1m (ref)	-1,082	-1,102	-1,119	-1,077	-1,092	-1,102
SWL -1.2m	-1,253	-1,274	-1,289	-1,252	-1,265	-1,275
SWL -1.5m	-1,519	-1,542	-1,560	-1,523	-1,538	-1,550
Impact factor ΔSWL=-0.2m	0,85	0,86	0,85	0,88	0,86	0,86
Impact factor ΔSWL=0.5m	0,87	0,88	0,88	0,89	0,89	0,90

B.5 Different sand ‘top soil’ (O1)



STRONG						
Resistance = 10d	Soil profile C					
	Mid parcel			Edge parcel		
Regional head	High +3	Neutral	Low -2	High +3	Neutral	Low -2
SWL -1m (ref)	-1,082	-1,190	-1,282	-1,033	-1,072	-1,101
SWL -1.2m	-1,158	-1,298	-1,432	-1,183	-1,237	-1,279
SWL -1.5m	-1,277	-1,489	-1,751	-1,410	-1,496	-1,575
▨	▨	▨	▨	▨	▨	▨
Impact factor ΔSWL=-0.2m	0,38	0,54	0,75	0,75	0,83	0,89
Impact factor ΔSWL=0.5m	0,39	0,60	0,94	0,75	0,85	0,95

WEAK						
Resistance = 1000d	Soil profile C					
	Mid parcel			Edge parcel		
Regional head	High +3	Neutral	Low -2	High +3	Neutral	Low -2
SWL -1m (ref)	-1,118	-1,189	-1,245	-1,047	-1,071	-1,089
SWL -1.2m	-1,205	-1,302	-1,382	-1,202	-1,238	-1,264
SWL -1.5m	-1,350	-1,503	-1,659	-1,437	-1,501	-1,552
▨	▨	▨	▨	▨	▨	▨
Impact factor ΔSWL=-0.2m	0,44	0,57	0,68	0,78	0,84	0,88
Impact factor ΔSWL=0.5m	0,46	0,63	0,83	0,78	0,86	0,93

B.6 Different clay ‘top soil’ (O11)

STRONG

Resistance = 10d	Soil profile A					
	Mid parcel			Edge parcel		
Regional head	High +3	Neutral	Low -2	High +3	Neutral	Low -2
SWL -1m (ref)	-0,512	-1,125	-2,649	-0,664	-1,079	-1,658
SWL -1.2m	-0,513	-1,125	-2,651	-0,715	-1,187	-1,815
SWL -1.5m	-0,512	-1,126	-2,654	-0,794	-1,337	-2,043
Impact factor ΔSWL=-0.2m	0,01	0,00	0,01	0,26	0,54	0,79
Impact factor ΔSWL=0.5m	0,00	0,00	0,01	0,26	0,52	0,77

Resistance = 10d	Soil profile B					
	Mid parcel			Edge parcel		
Regional head	High +0.5	Neutral	Low -0.5	High +0.5	Neutral	Low -0.5
SWL -1m (ref)	-0,715	-1,035	-1,418	-0,797	-1,032	-1,308
SWL -1.2m	-0,740	-1,066	-1,453	-0,857	-1,104	-1,393
SWL -1.5m	-0,775	-1,114	-1,505	-0,947	-1,207	-1,504
Impact factor ΔSWL=-0.2m	0,13	0,16	0,18	0,30	0,36	0,43
Impact factor ΔSWL=0.5m	0,12	0,16	0,17	0,30	0,35	0,39

Resistance = 10d	Soil profile C					
	Mid parcel			Edge parcel		
Regional head	High +3	Neutral	Low -2	High +3	Neutral	Low -2
SWL -1m (ref)	-1,172	-1,335	-1,459	-1,062	-1,115	-1,149
SWL -1.2m	-1,300	-1,482	-1,645	-1,238	-1,297	-1,333
SWL -1.5m	-1,449	-1,704	-2,335	-1,480	-1,568	-1,626
Impact factor ΔSWL=-0.2m	0,64	0,74	0,93	0,88	0,91	0,92
Impact factor ΔSWL=0.5m	0,55	0,74	1,75	0,84	0,91	0,95

Resistance = 10d	Soil profile D					
	Mid parcel			Edge parcel		
Regional head	High +3	Neutral	Low -2	High +3	Neutral	Low -2
SWL -1m (ref)	-1,011	-1,038	-1,058	-1,016	-1,034	-1,048
SWL -1.2m	-1,188	-1,218	-1,237	-1,196	-1,216	-1,229
SWL -1.5m	-1,469	-1,499	-1,519	-1,479	-1,500	-1,515
Impact factor ΔSWL=-0.2m	0,89	0,90	0,90	0,90	0,91	0,91
Impact factor ΔSWL=0.5m	0,92	0,92	0,92	0,93	0,93	0,93

WEAK

Resistance = 1000d	Soil profile A					
	Mid parcel			Edge parcel		
Regional head	High +3	Neutral	Low -2	High +3	Neutral	Low -2
SWL -1m (ref)	-0,579	-1,108	-2,121	-0,732	-1,074	-1,49
SWL -1.2m	-0,581	-1,115	-2,148	-0,797	-1,185	-1,643
SWL -1.5m	-0,582	-1,117	-2,171	-0,895	-1,337	-1,862
Impact factor ΔSWL=-0.2m	0,01	0,03	0,14	0,33	0,56	0,77
Impact factor ΔSWL=0.5m	0,01	0,02	0,10	0,33	0,53	0,74

Resistance = 1000d	Soil profile B					
	Mid parcel			Edge parcel		
Regional head	High +0.5	Neutral	Low -0.5	High +0.5	Neutral	Low -0.5
SWL -1m (ref)	-1,015	-1,036	-1,058	-1,017	-1,033	-1,048
SWL -1.2m	-1,187	-1,211	-1,230	-1,194	-1,212	-1,226
SWL -1.5m	-1,460	-1,478	-1,499	-1,470	-1,484	-1,500
Impact factor ΔSWL=-0.2m	0,86	0,88	0,86	0,89	0,90	0,89
Impact factor ΔSWL=0.5m	0,89	0,88	0,88	0,91	0,90	0,90

Resistance = 1000d	Soil profile C					
	Mid parcel			Edge parcel		
Regional head	High +3	Neutral	Low -2	High +3	Neutral	Low -2
SWL -1m (ref)	-1,237	-1,339	-1,411	-1,083	-1,116	-1,137
SWL -1.2m	-1,367	-1,490	-1,590	-1,261	-1,299	-1,325
SWL -1.5m	-1,542	-1,727	-1,946	-1,516	-1,574	-1,613
Impact factor ΔSWL=-0.2m	0,65	0,76	0,90	0,89	0,91	0,94
Impact factor ΔSWL=0.5m	0,61	0,78	1,07	0,87	0,92	0,95

Resistance = 1000d	Soil profile D					
	Mid parcel			Edge parcel		
Regional head	High +3	Neutral	Low -2	High +3	Neutral	Low -2
SWL -1m (ref)	-1,015	-1,038	-1,058	-1,019	-1,034	-1,048
SWL -1.2m	-1,194	-1,218	-1,234	-1,200	-1,217	-1,228
SWL -1.5m	-1,475	-1,500	-1,516	-1,483	-1,501	-1,513
Impact factor ΔSWL=-0.2m	0,90	0,90	0,88	0,91	0,92	0,90
Impact factor ΔSWL=0.5m	0,92	0,92	0,92	0,93	0,93	0,93

B.7 Peat instead of clay confining layer

STRONG

Resistance = 10d	Soil profile A					
	Mid parcel			Edge parcel		
Regional head	High +3	Neutral	Low -2	High +3	Neutral	Low -2
SWL -1m (ref)	-0,828	-1,514	-2,762	-1,001	-1,245	-1,487
SWL -1.2m	-0,828	-1,522	-2,783	-1,085	-1,376	-1,671
SWL -1.5m	-0,831	-1,536	-2,811	-1,197	-1,557	-1,945
Impact factor ΔSWL=-0.2m	0,00	0,04	0,11	0,42	0,65	0,92
Impact factor ΔSWL=0.5m	0,01	0,04	0,10	0,39	0,62	0,92

Resistance = 10d	Soil profile B					
	Mid parcel			Edge parcel		
Regional head	High +0.5	Neutral	Low -0.5	High +0.5	Neutral	Low -0.5
SWL -1m (ref)	-0,940	-1,180	-1,482	-1,000	-1,146	-1,324
SWL -1.2m	-0,956	-1,201	-1,509	-1,060	-1,226	-1,425
SWL -1.5m	-0,986	-1,242	-1,553	-1,144	-1,324	-1,549
Impact factor ΔSWL=-0.2m	0,08	0,11	0,14	0,30	0,40	0,51
Impact factor ΔSWL=0.5m	0,09	0,12	0,14	0,29	0,36	0,45

Resistance = 10d	Soil profile C					
	Mid parcel			Edge parcel		
Regional head	High +3	Neutral	Low -2	High +3	Neutral	Low -2
SWL -1m (ref)	-1,170	-1,333	-1,454	-1,062	-1,114	-1,148
SWL -1.2m	-1,212	-1,479	-1,640	-1,217	-1,296	-1,337
SWL -1.5m	-1,447	-1,697	-2,251	-1,479	-1,566	-1,625
Impact factor ΔSWL=-0.2m	0,21	0,73	0,93	0,78	0,91	0,95
Impact factor ΔSWL=0.5m	0,55	0,73	1,59	0,83	0,90	0,95

Resistance = 10d	Soil profile D					
	Mid parcel			Edge parcel		
Regional head	High +3	Neutral	Low -2	High +3	Neutral	Low -2
SWL -1m (ref)	-1,182	-1,200	-1,215	-1,147	-1,159	-1,169
SWL -1.2m	-1,314	-1,337	-1,351	-1,298	-1,311	-1,322
SWL -1.5m	-1,537	-1,566	-1,582	-1,538	-1,556	-1,567
Impact factor ΔSWL=-0.2m	0,66	0,69	0,68	0,76	0,76	0,77
Impact factor ΔSWL=0.5m	0,71	0,73	0,73	0,78	0,79	0,80

WEAK

Resistance = 1000d	Soil profile A					
	Mid parcel			Edge parcel		
Regional head	High +3	Neutral	Low -2	High +3	Neutral	Low -2
SWL -1m (ref)	-0,967	-1,538	-2,394	-1,068	-1,247	-1,432
SWL -1.2m	-0,972	-1,554	-2,443	-1,165	-1,388	-1,606
SWL -1.5m	-0,978	-1,592	-2,511	-1,299	-1,579	-1,871
Impact factor ΔSWL=-0.2m	0,03	0,08	0,25	0,49	0,70	0,87
Impact factor ΔSWL=0.5m	0,02	0,11	0,23	0,46	0,66	0,88

Resistance = 1000d	Soil profile B					
	Mid parcel			Edge parcel		
Regional head	High +0.5	Neutral	Low -0.5	High +0.5	Neutral	Low -0.5
SWL -1m (ref)	-1,180	-1,199	-1,211	-1,146	-1,147	-1,168
SWL -1.2m	-1,311	-1,328	-1,345	-1,295	-1,307	-1,318
SWL -1.5m	-1,525	-1,547	-1,574	-1,528	-1,544	-1,563
Impact factor ΔSWL=-0.2m	0,66	0,65	0,67	0,75	0,80	0,75
Impact factor ΔSWL=0.5m	0,69	0,70	0,73	0,76	0,79	0,79

Resistance = 1000d	Soil profile C					
	Mid parcel			Edge parcel		
Regional head	High +3	Neutral	Low -2	High +3	Neutral	Low -2
SWL -1m (ref)	-1,229	-1,334	-1,407	-1,082	-1,114	-1,135
SWL -1.2m	-1,366	-1,484	-1,581	-1,261	-1,298	-1,323
SWL -1.5m	-1,538	-1,718	-1,915	-1,515	-1,572	-1,610
Impact factor ΔSWL=-0.2m	0,69	0,75	0,87	0,89	0,92	0,94
Impact factor ΔSWL=0.5m	0,62	0,77	1,02	0,87	0,92	0,95

Resistance = 1000d	Soil profile D					
	Mid parcel			Edge parcel		
Regional head	High +3	Neutral	Low -2	High +3	Neutral	Low -2
SWL -1m (ref)	-1,185	-1,201	-1,215	-1,149	-1,159	-1,168
SWL -1.2m	-1,318	-1,337	-1,350	-1,300	-1,311	-1,319
SWL -1.5m	-1,542	-1,567	-1,580	-1,544	-1,557	-1,565
Impact factor ΔSWL=-0.2m	0,67	0,68	0,68	0,76	0,76	0,76
Impact factor ΔSWL=0.5m	0,71	0,73	0,73	0,79	0,80	0,79

B.8 Thinner top soil

STRONG

Resistance = 10d	Soil profile B					
	Mid parcel			Edge parcel		
Regional head	High +0.5	Neutral	Low -0.5	High +0.5	Neutral	Low -0.5
SWL -1m (ref)	-0,772	-1,051	-1,394	-0,846	-1,050	-1,291
SWL -1.2m	-0,800	-1,094	-1,437	-0,910	-1,128	-1,377
SWL -1.5m	-0,848	-1,150	-1,503	-0,995	-1,237	-1,502
Impact factor ΔSWL=-0.2m	0,14	0,22	0,22	0,32	0,39	0,43
Impact factor ΔSWL=0.5m	0,15	0,20	0,22	0,30	0,37	0,42

Resistance = 10d	Soil profile C					
	Mid parcel			Edge parcel		
Regional head	High +3	Neutral	Low -2	High +3	Neutral	Low -2
SWL -1m (ref)	-1,266	-1,675	-2,383	-1,089	-1,142	-1,165
SWL -1.2m	-1,358	-1,752	-2,629	-1,261	-1,316	-1,338
SWL -1.5m	-1,405	-1,765	-2,768	-1,468	-1,704	-2,121
Impact factor ΔSWL=-0.2m	0,46	0,39	1,23	0,86	0,87	0,87
Impact factor	0,28	0,18	0,77	0,76	1,12	1,91

Resistance = 10d	Soil profile D					
	Mid parcel			Edge parcel		
Regional head	High +3	Neutral	Low -2	High +3	Neutral	Low -2
SWL -1m (ref)	-1,045	-1,063	-1,075	-1,046	-1,056	-1,064
SWL -1.2m	-1,211	-1,232	-1,246	-1,214	-1,228	-1,238
SWL -1.5m	-1,482	-1,505	-1,520	-1,488	-1,503	-1,514
Impact factor ΔSWL=-0.2m	0,83	0,85	0,86	0,84	0,86	0,87
Impact factor ΔSWL=0.5m	0,87	0,88	0,89	0,88	0,89	0,90

WEAK

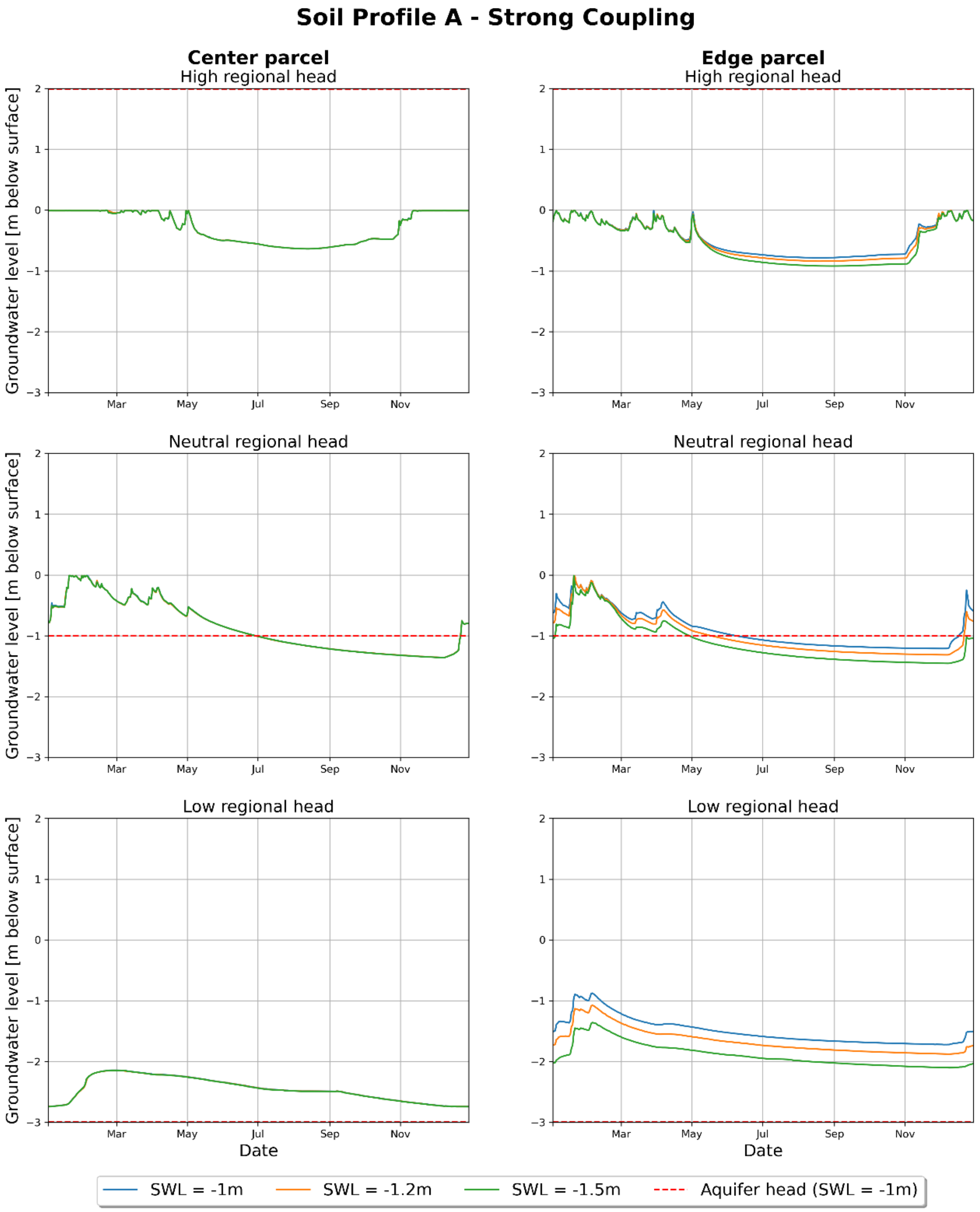
Resistance = 1000d	Soil profile B					
	Mid parcel			Edge parcel		
Regional head	High +0.5	Neutral	Low -0.5	High +0.5	Neutral	Low -0.5
SWL -1m (ref)	-1,046	-1,062	-1,073	-1,046	-1,057	-1,065
SWL -1.2m	-1,208	-1,224	-1,240	-1,212	-1,223	-1,235
SWL -1.5m	-1,471	-1,489	-1,506	-1,479	-1,492	-1,505
Impact factor ΔSWL=-0.2m	0,81	0,81	0,84	0,83	0,83	0,85
Impact factor ΔSWL=0.5m	0,85	0,85	0,87	0,87	0,87	0,88

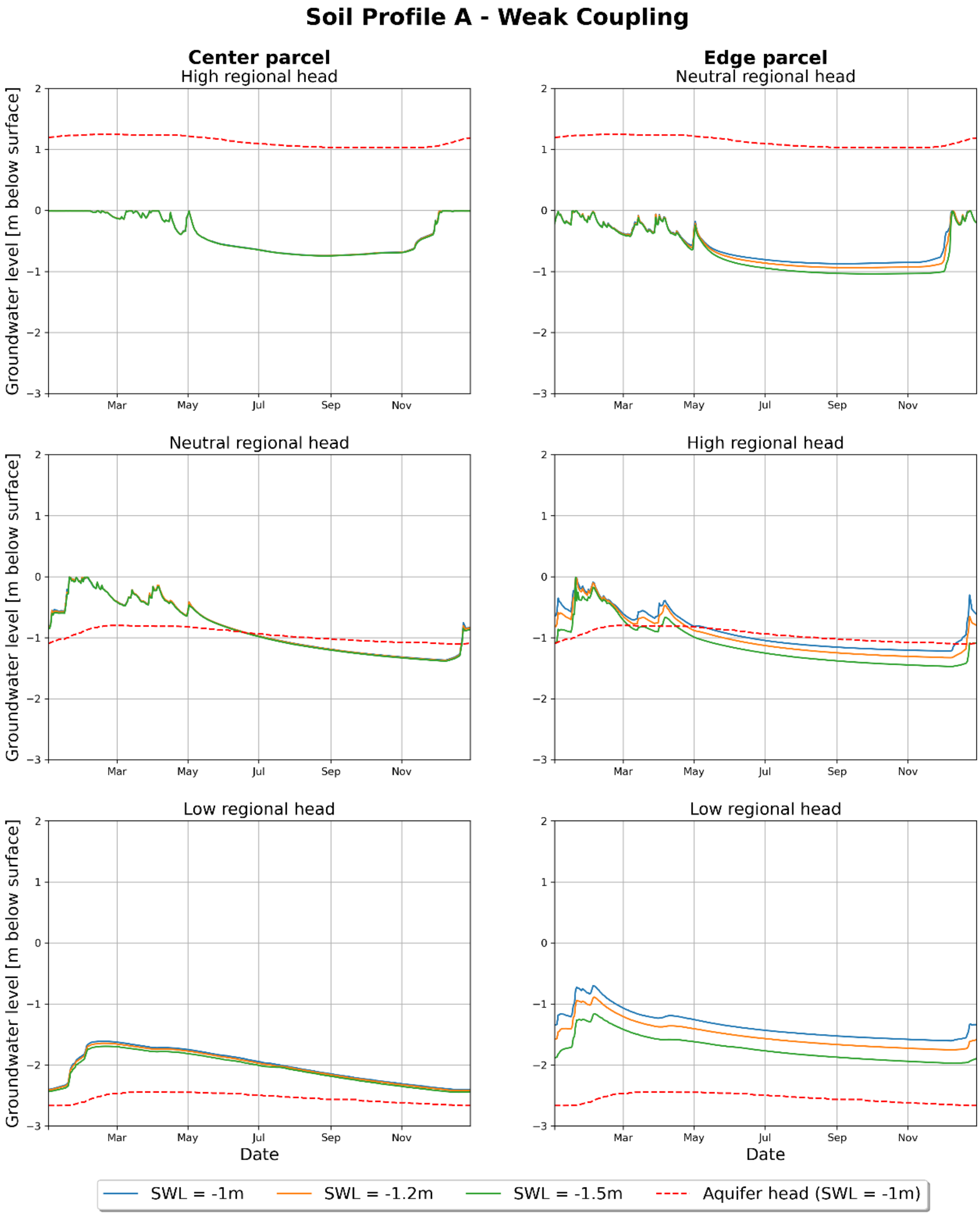
Resistance = 1000d	Soil profile C					
	Mid parcel			Edge parcel		
Regional head	High +3	Neutral	Low -2	High +3	Neutral	Low -2
SWL -1m (ref)	-1,374	-1,680	-2,056	-1,112	-1,143	-1,158
SWL -1.2m	-1,488	-1,785	-2,296	-1,287	-1,318	-1,332
SWL -1.5m	-1,524	-1,820	-2,464	-1,549	-1,735	-2,003
Impact factor ΔSWL=-0.2m	0,57	0,53	1,20	0,87	0,88	0,87
Impact factor	0,30	0,28	0,82	0,87	1,18	1,69

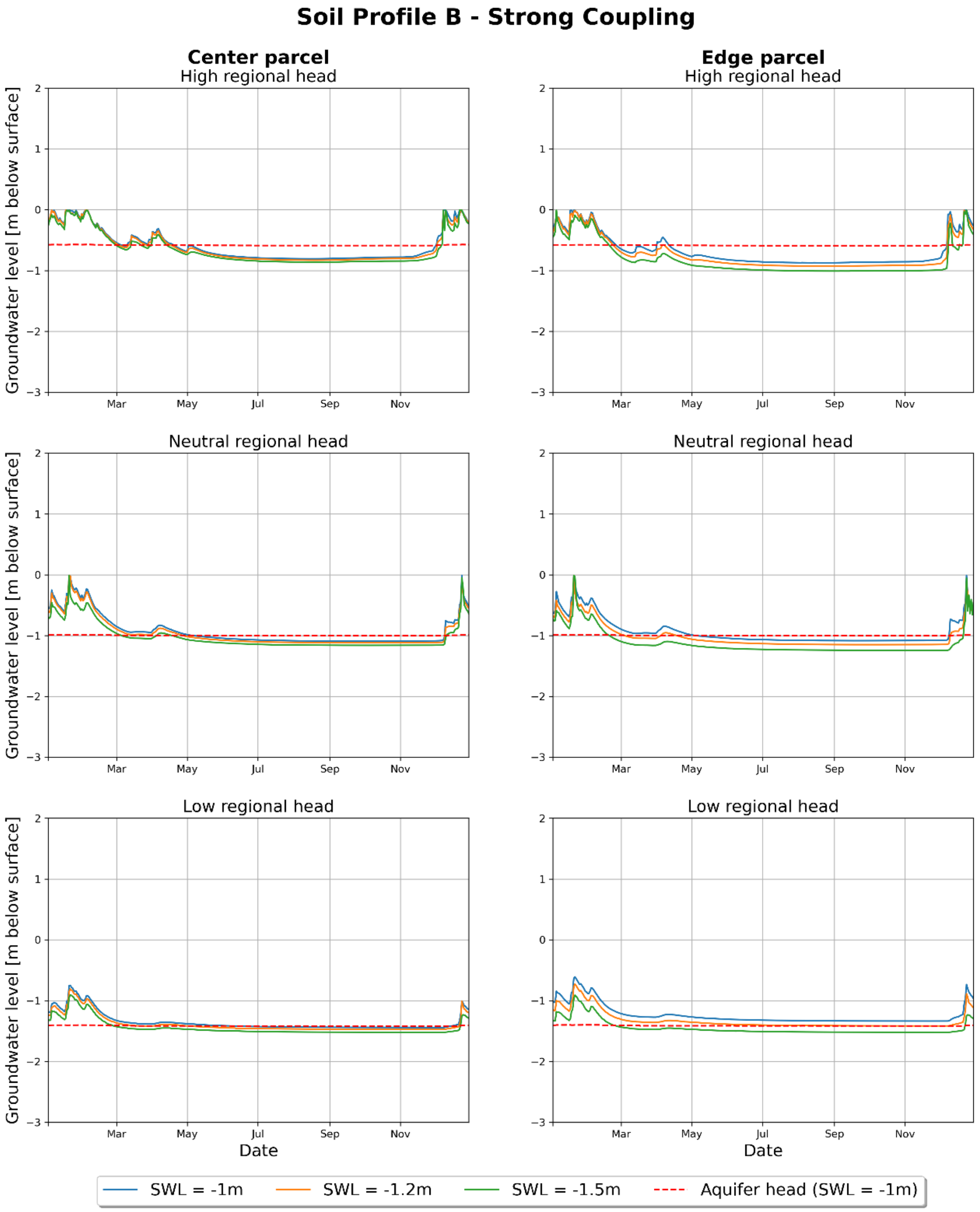
Resistance = 1000d	Soil profile D					
	Mid parcel			Edge parcel		
Regional head	High +3	Neutral	Low -2	High +3	Neutral	Low -2
SWL -1m (ref)	-1,048	-1,063	-1,074	-1,048	-1,056	-1,063
SWL -1.2m	-1,215	-1,232	-1,245	-1,217	-1,228	-1,237
SWL -1.5m	-1,487	-1,506	-1,519	-1,491	-1,504	-1,513
Impact factor ΔSWL=-0.2m	0,84	0,85	0,86	0,85	0,86	0,87
Impact factor ΔSWL=0.5m	0,88	0,89	0,89	0,89	0,90	0,90

Appendix C1 Results (base set) – GWT and hydraulic head time series

This appendix presents graphics of the GWT time series for the third year (2018). Left: centre of the parcel. Right: ‘edge’ of the parcel. The hydraulic head in the deep aquifer is depicted as well (only for the reference SWL). The difference between the aquifer head and GWT indicates if upward or downward seepage conditions prevail and the extent to which the aquifer head adjusts to the GWT changes (most apparent for weak coupling).




Soil Profile A - Weak Coupling
Center parcel
High regional head
Edge parcel
Neutral regional head
Neutral regional head
High regional head
Low regional head
Low regional head
Groundwater level [m below surface]
2
1
0
−1
−2
−3
Mar
May
Jul
Sep
Nov
Date
SWL = -1m
SWL = -1.2m
SWL = -1.5m
Aquifer head (SWL = -1m)



Soil Profile B - Strong Coupling

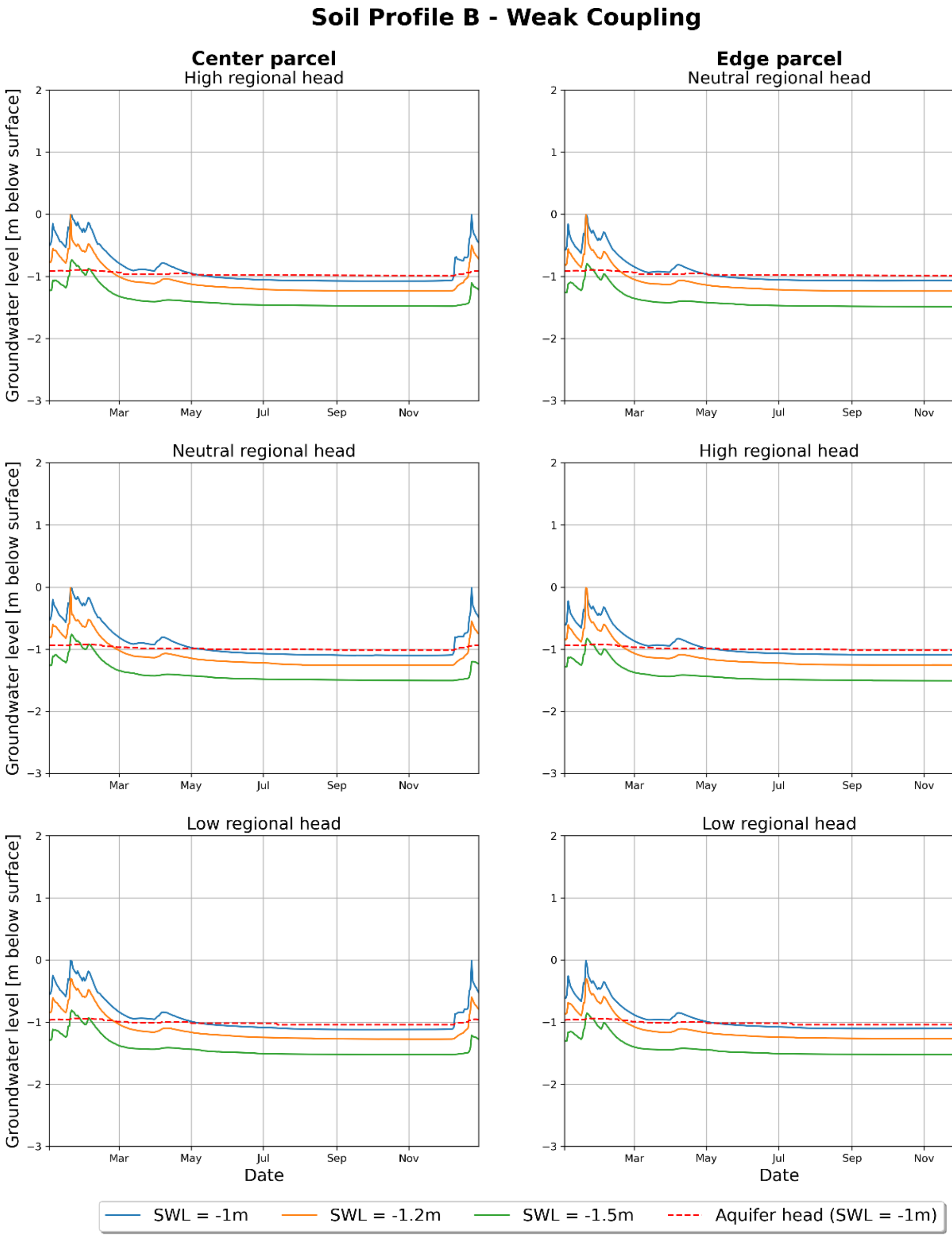
Center parcel

Edge parcel

High regional head

Neutral regional head

Low regional head



Soil Profile B - Weak Coupling

Center parcel

High regional head

Edge parcel

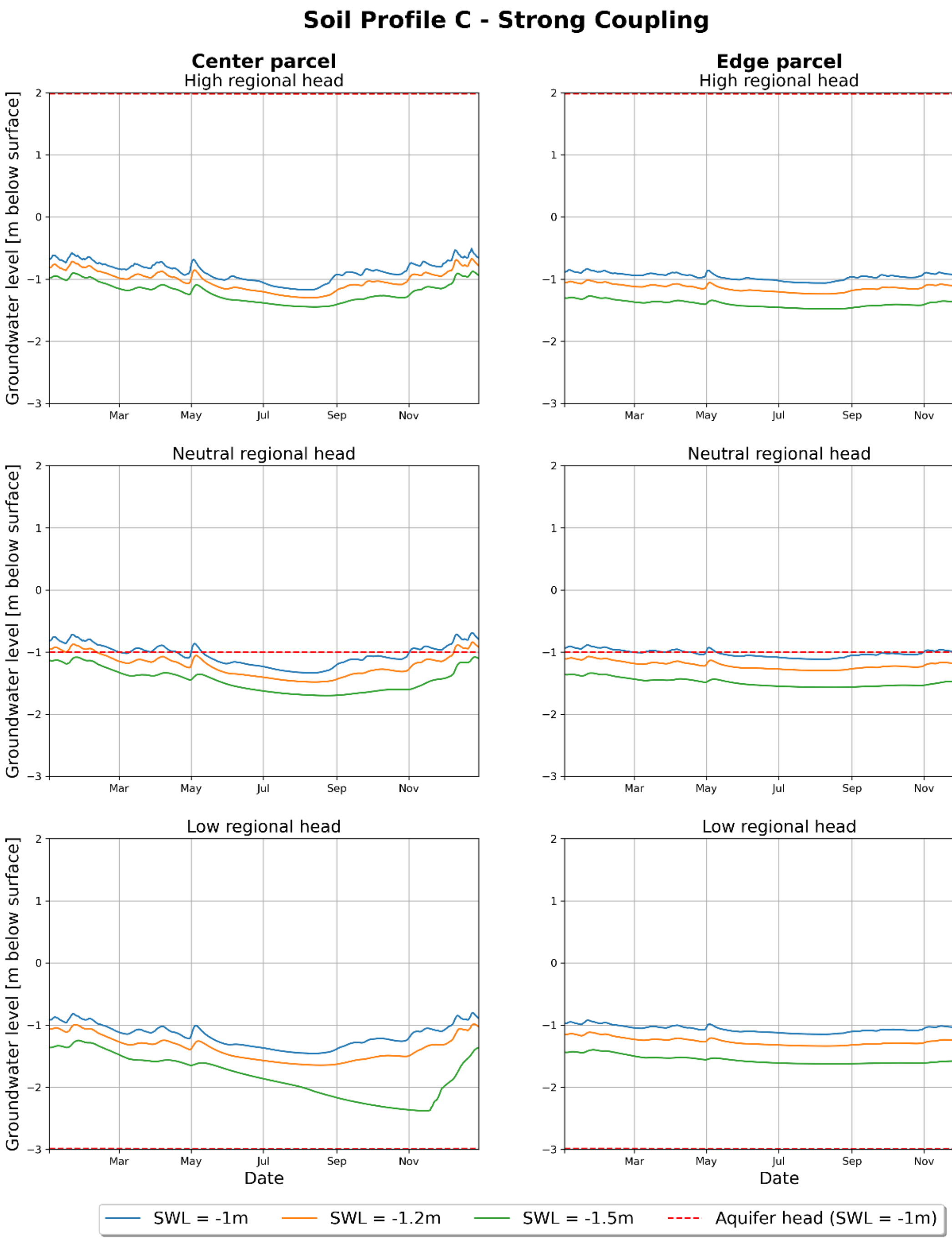
Neutral regional head

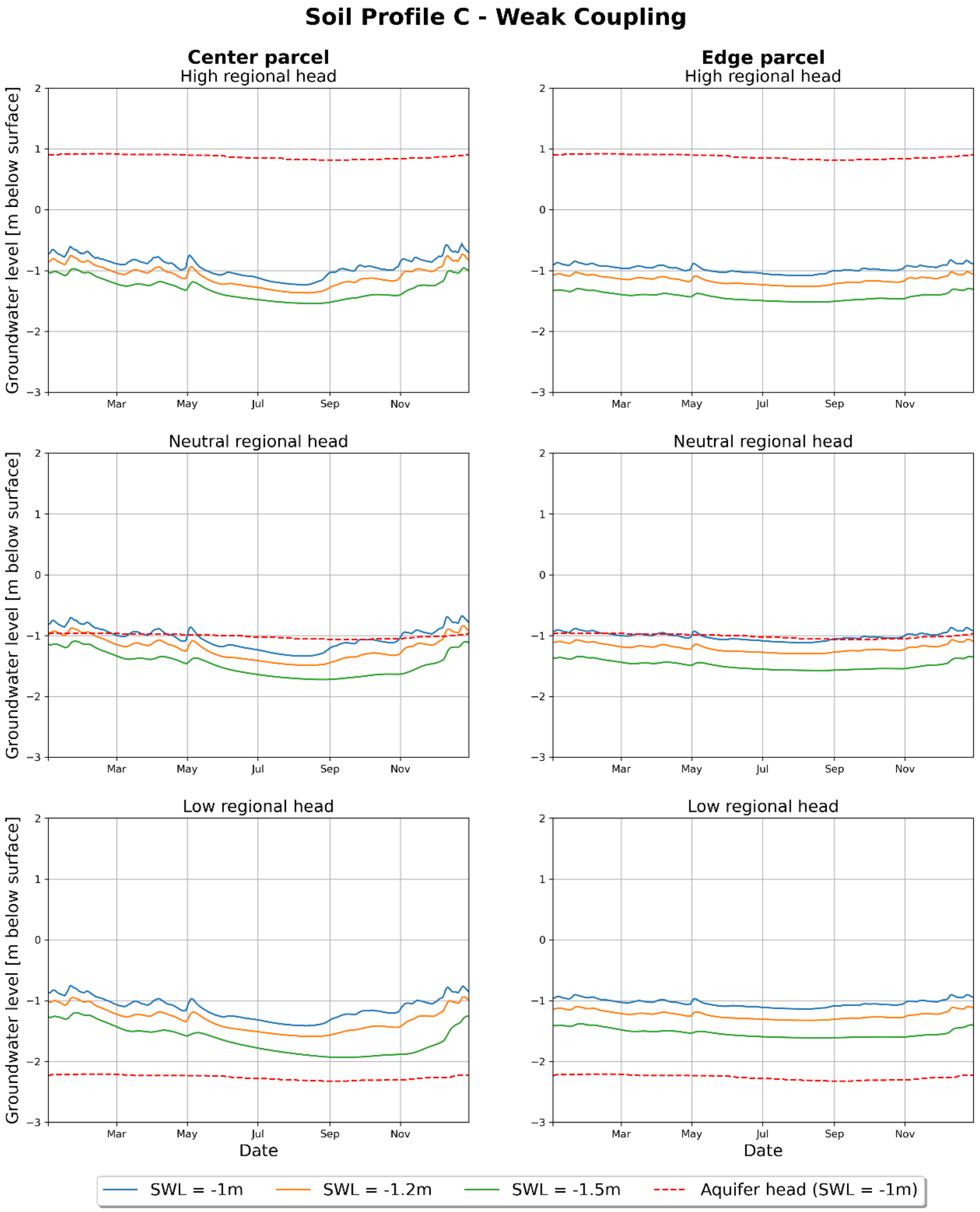
Neutral regional head

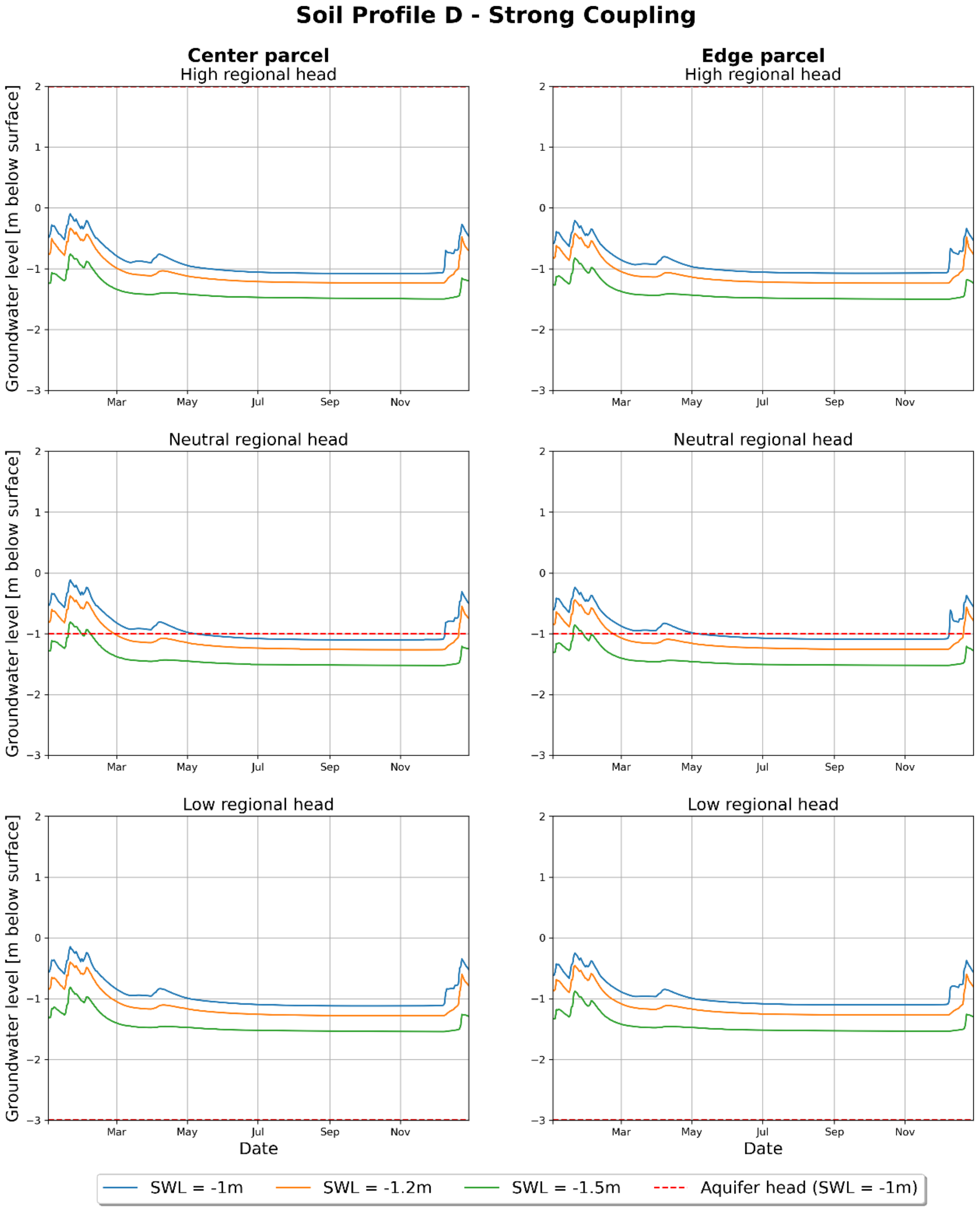
High regional head

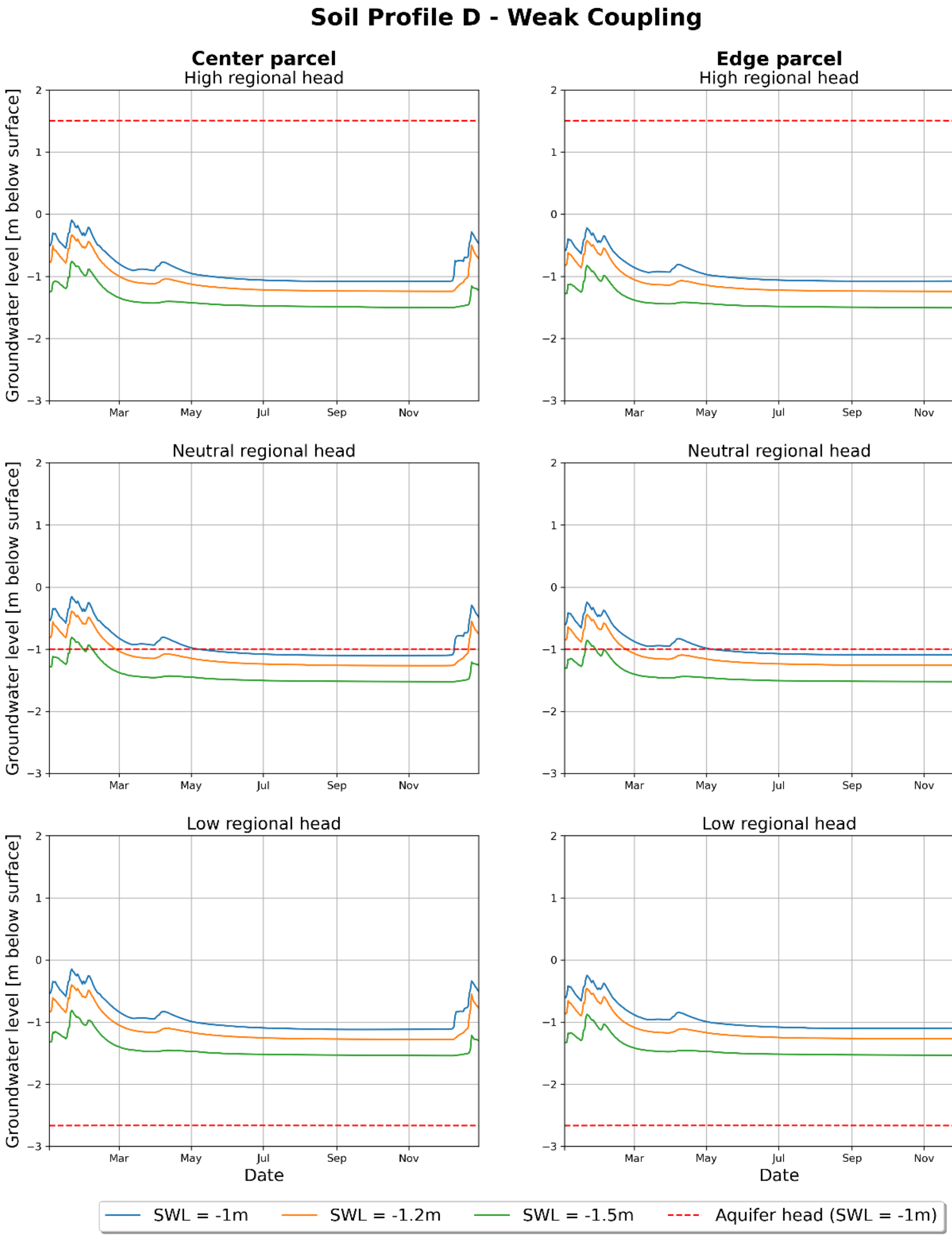
Low regional head

Low regional head


Soil Profile C - Strong Coupling
Center parcel
Edge parcel
High regional head
Neutral regional head
Low regional head
Groundwater level [m below surface]
2
1
0
−1
−2
−3
Mar
May
Jul
Sep
Nov
Date
SWL = -1m
SWL = -1.2m
SWL = -1.5m
Aquifer head (SWL = -1m)

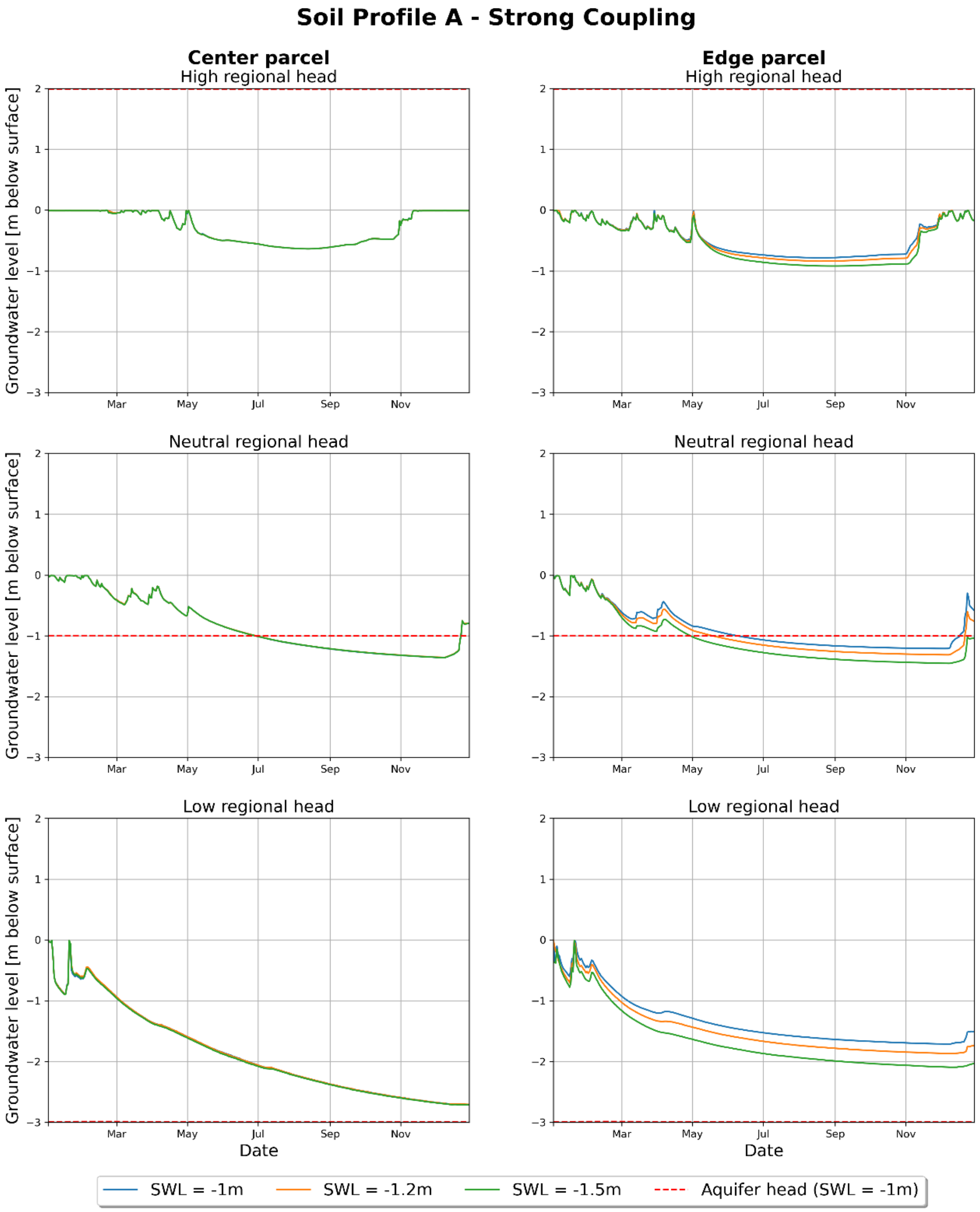

Soil Profile C - Weak Coupling
Center parcel
High regional head
Edge parcel
High regional head
Neutral regional head
Neutral regional head
Low regional head
Low regional head
Groundwater level [m below surface]
2
1
0
−1
−2
−3
Mar
May
Jul
Sep
Nov
Date
SWL = -1m
SWL = -1.2m
SWL = -1.5m
Aquifer head (SWL = -1m)

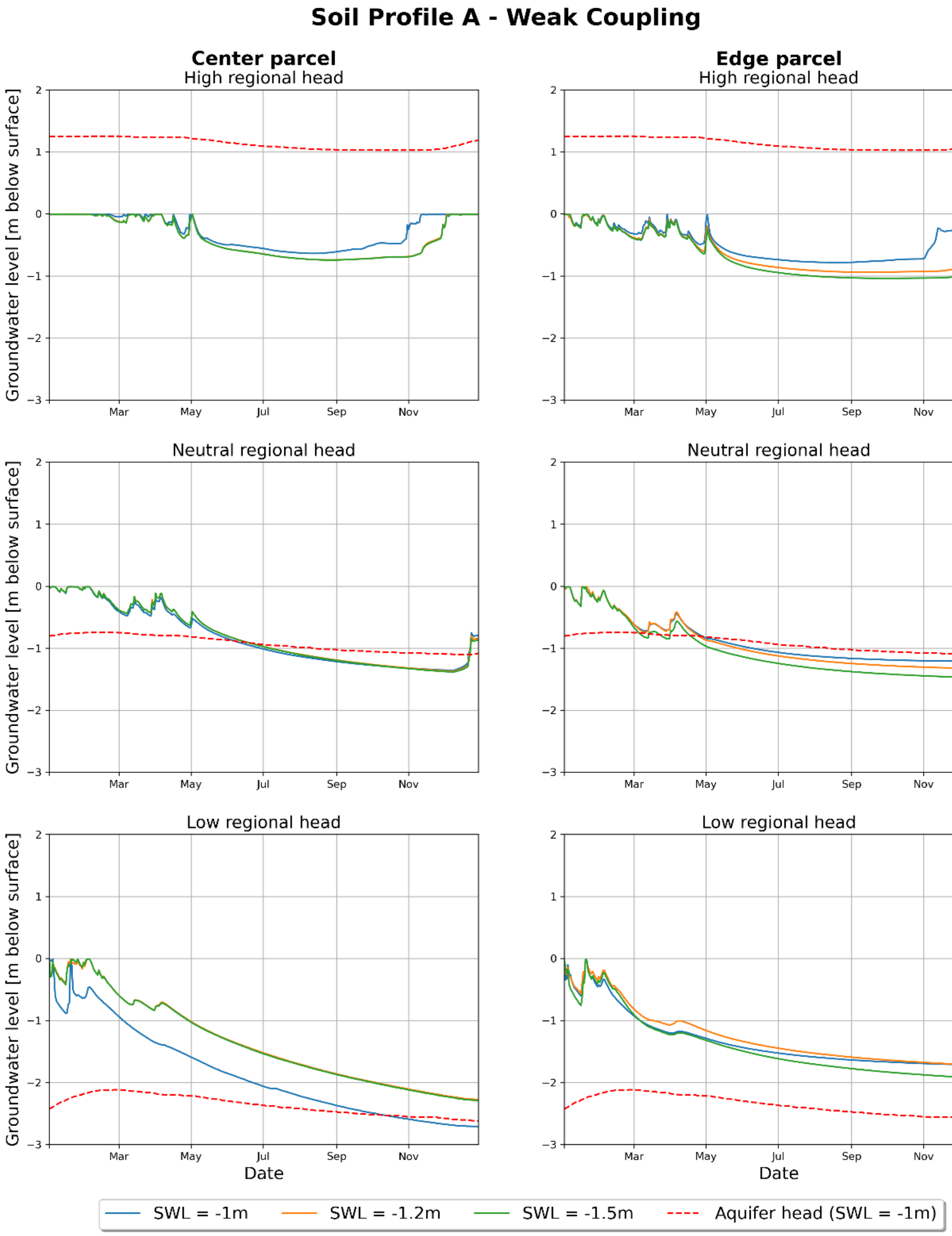

Soil Profile D - Strong Coupling
Center parcel
Edge parcel
High regional head
Neutral regional head
Low regional head
Groundwater level [m below surface]
2
1
0
−1
−2
−3
Mar
May
Jul
Sep
Nov
Date
SWL = -1m
SWL = -1.2m
SWL = -1.5m
Aquifer head (SWL = -1m)

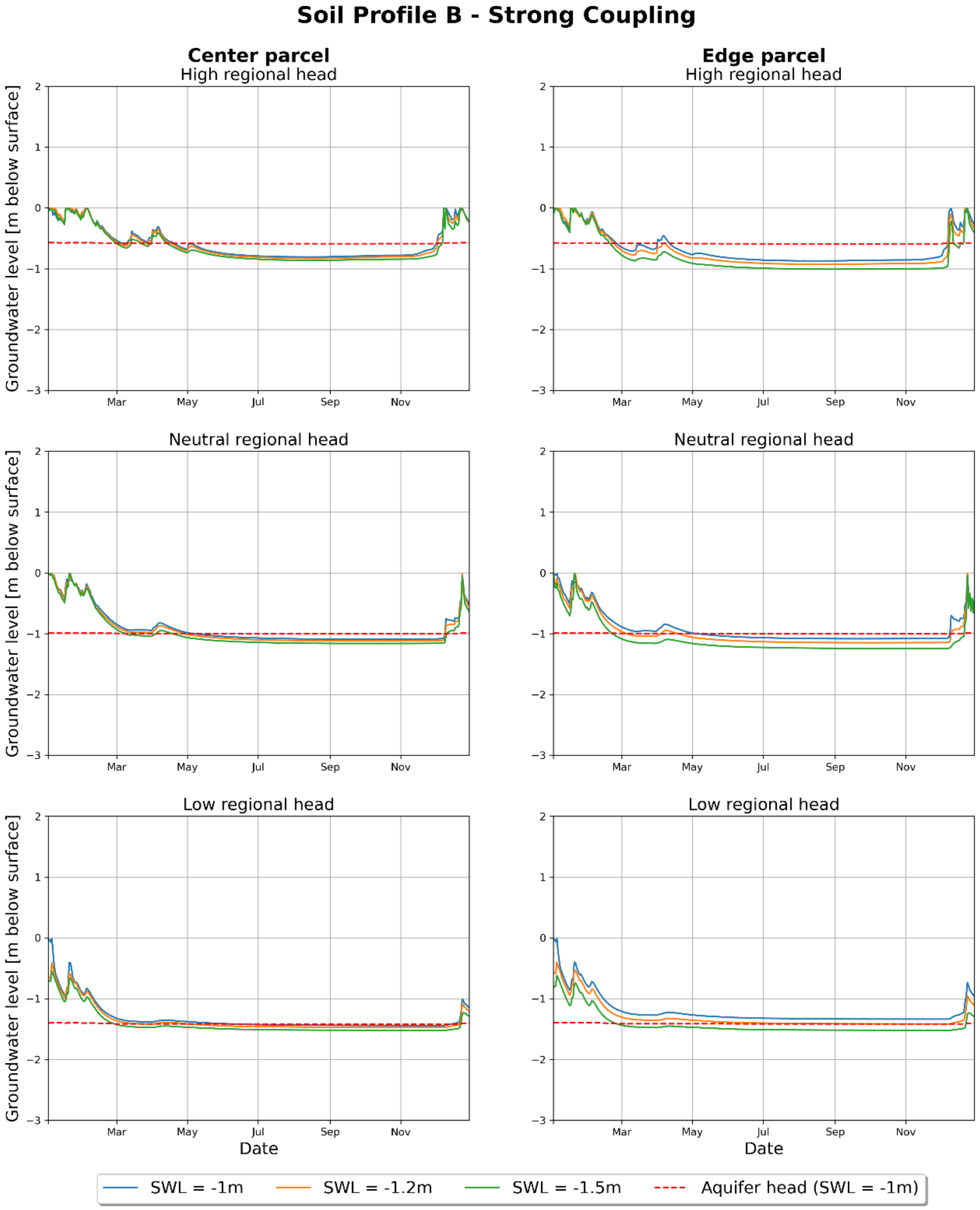

Soil Profile D - Weak Coupling
Center parcel
High regional head
Edge parcel
High regional head
Neutral regional head
Neutral regional head
Low regional head
Low regional head
Groundwater level [m below surface]
2
1
0
−1
−2
−3
Mar
May
Jul
Sep
Nov
Date
SWL = -1m
SWL = -1.2m
SWL = -1.5m
Aquifer head (SWL = -1m)

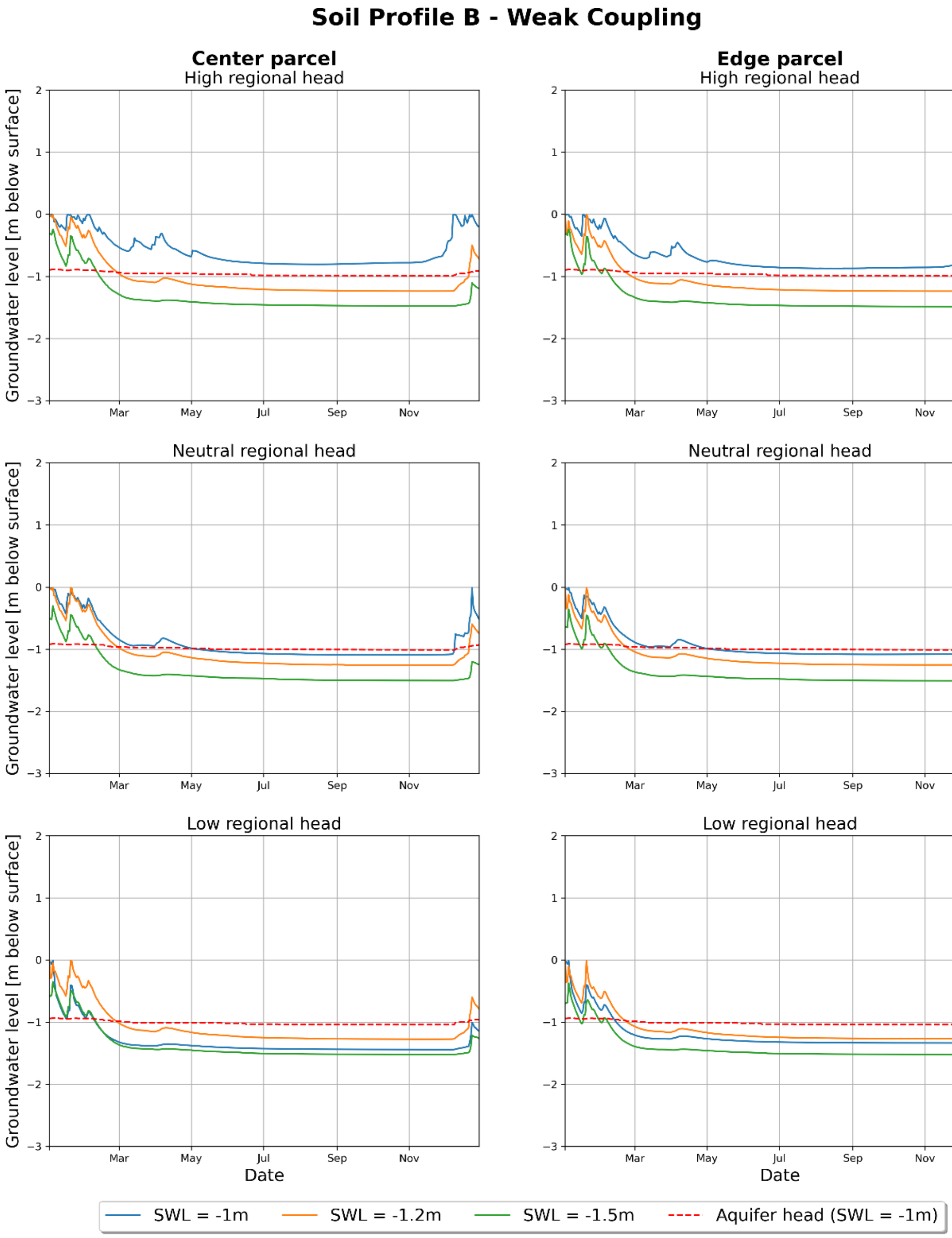
Appendix C2 Results (2016-2018 climate) – GWT and hydraulic head time series

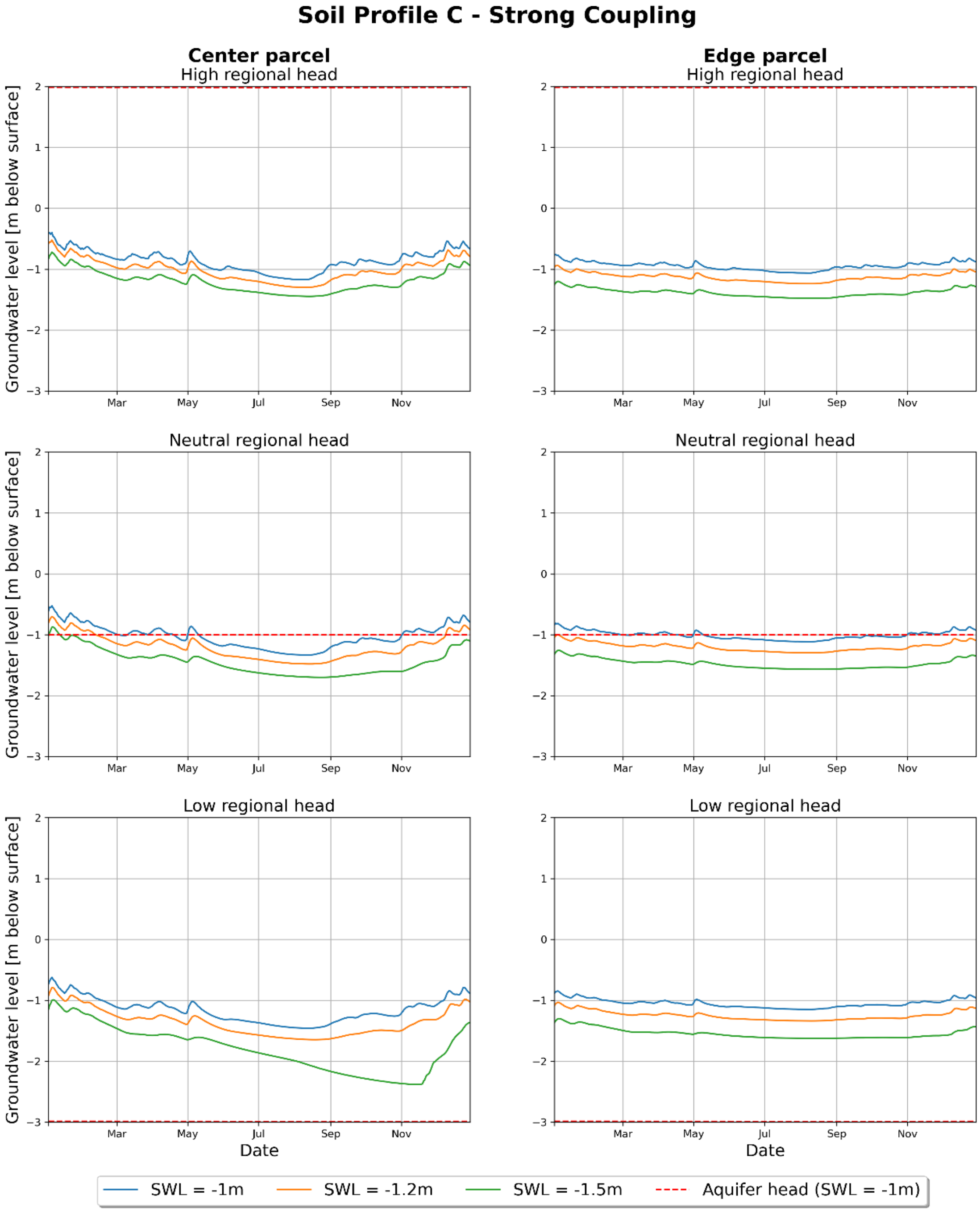
This appendix presents graphics of the GWT time series for the third year (2018). Left: centre of the parcel. Right: 'edge' of the parcel. The hydraulic head in the deep aquifer is depicted as well (only for the reference SWL). The difference between the aquifer head and GWT indicates if upward or downward seepage conditions prevail and the extent to which the aquifer head adjusts to the GWT changes (most apparent for weak coupling).

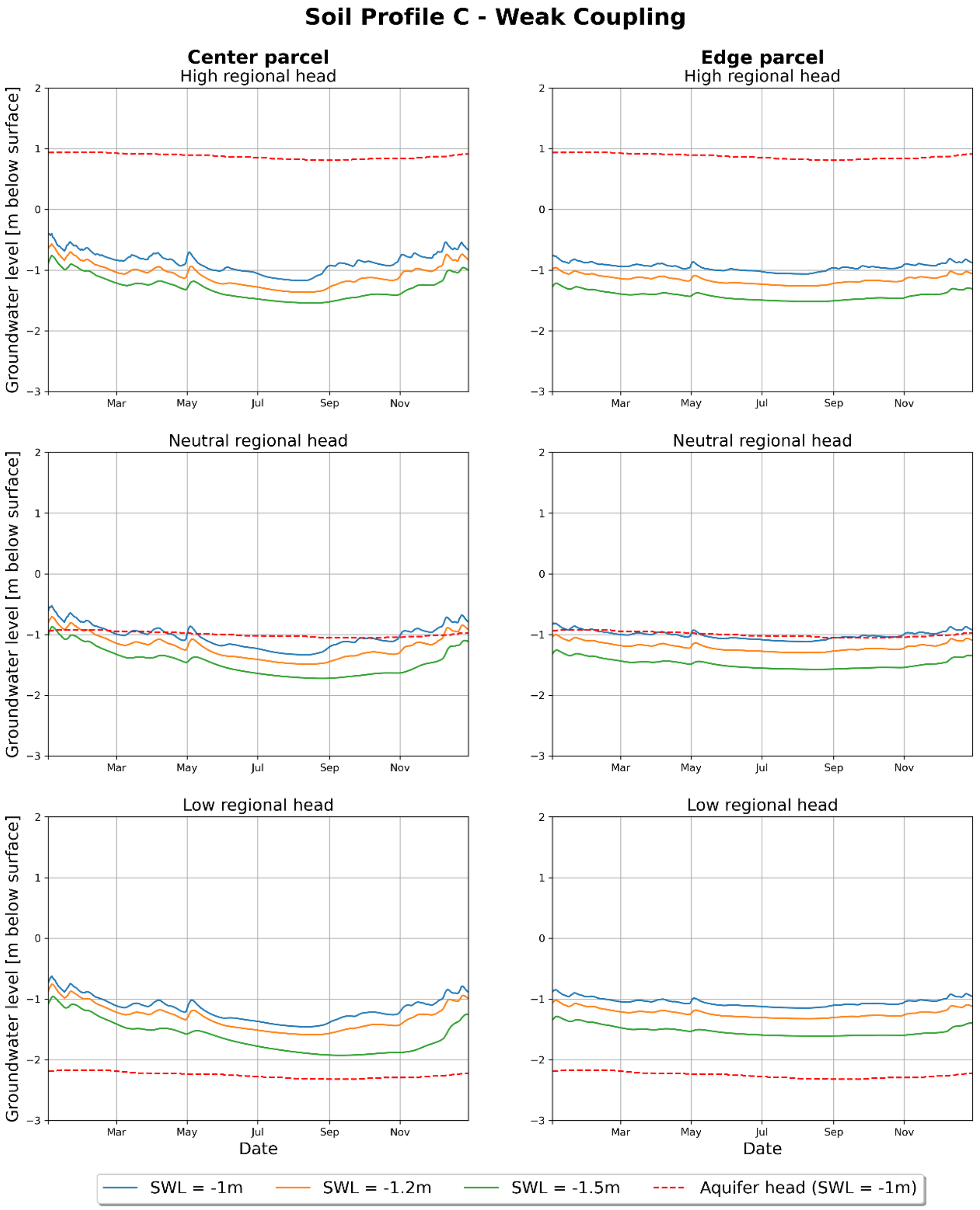


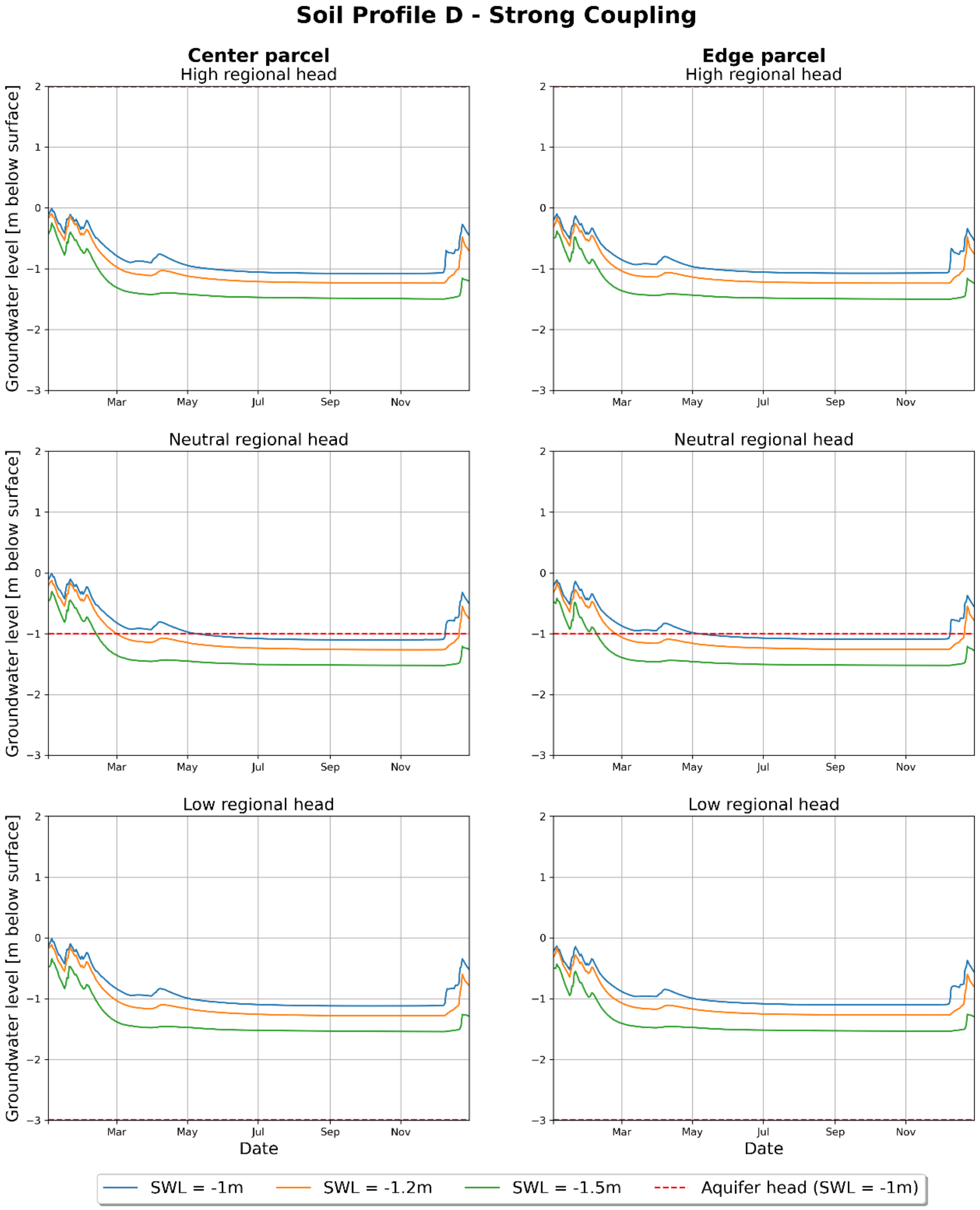

Soil Profile A - Weak Coupling
Center parcel
High regional head
Edge parcel
High regional head
Neutral regional head
Neutral regional head
Low regional head
Low regional head
Groundwater level [m below surface]
2
1
0
−1
−2
−3
Mar
May
Jul
Sep
Nov
Date
SWL = -1m
SWL = -1.2m
SWL = -1.5m
Aquifer head (SWL = -1m)

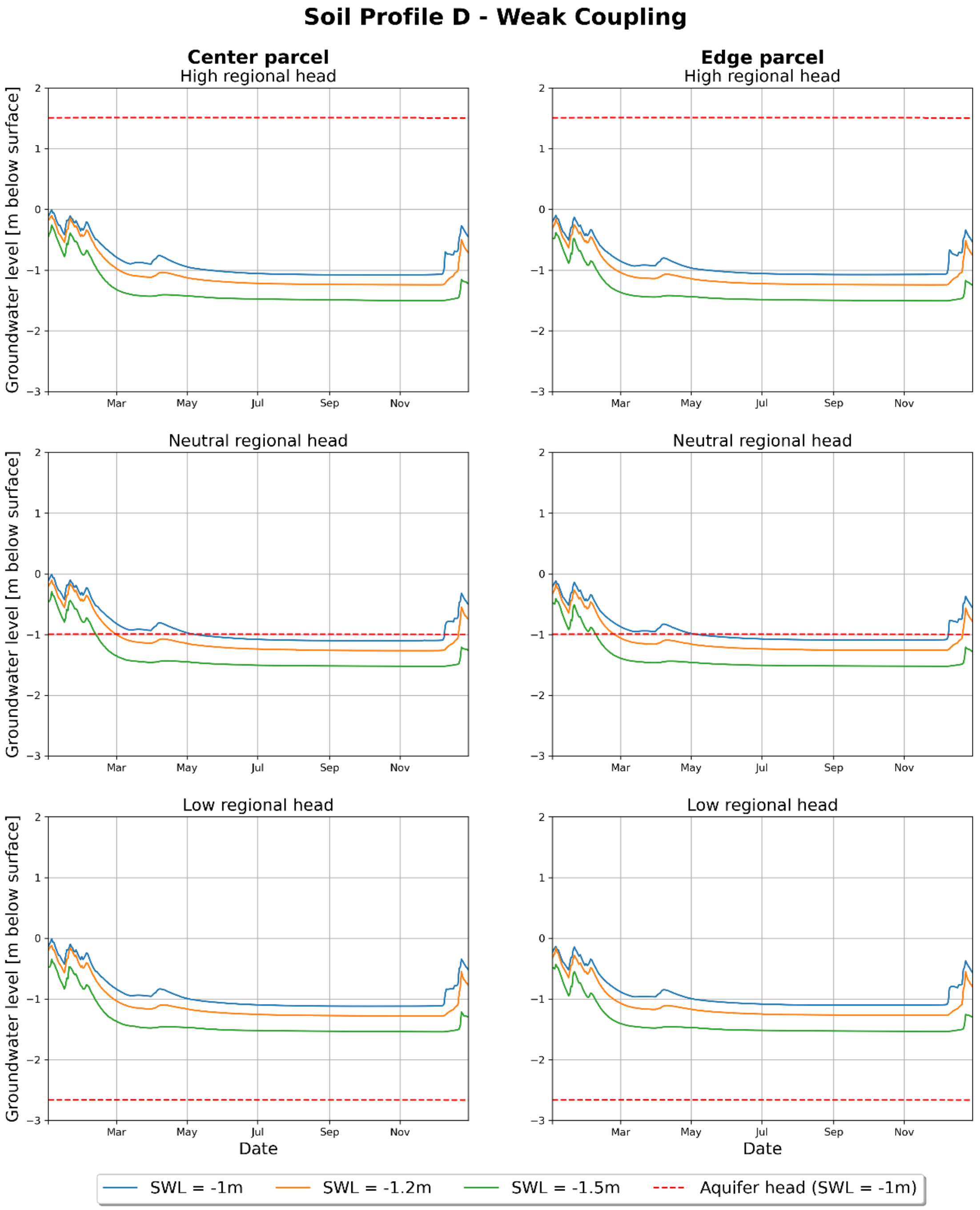

Soil Profile B - Strong Coupling
Center parcel
Edge parcel
High regional head
Neutral regional head
Low regional head
Groundwater level [m below surface]
Date
Mar
May
Jul
Sep
Nov
2
1
0
−1
−2
−3
SWL = -1m
SWL = -1.2m
SWL = -1.5m
Aquifer head (SWL = -1m)


Soil Profile B - Weak Coupling
Center parcel
High regional head
Edge parcel
High regional head
Neutral regional head
Neutral regional head
Low regional head
Low regional head
Groundwater level [m below surface]
2
1
0
−1
−2
−3
Mar
May
Jul
Sep
Nov
Date
SWL = -1m
SWL = -1.2m
SWL = -1.5m
Aquifer head (SWL = -1m)


Soil Profile C - Strong Coupling
Center parcel
High regional head
Edge parcel
High regional head
Neutral regional head
Neutral regional head
Low regional head
Low regional head
Groundwater level [m below surface]
2
1
0
−1
−2
−3
Mar
May
Jul
Sep
Nov
Date
Date
SWL = -1m
SWL = -1.2m
SWL = -1.5m
Aquifer head (SWL = -1m)

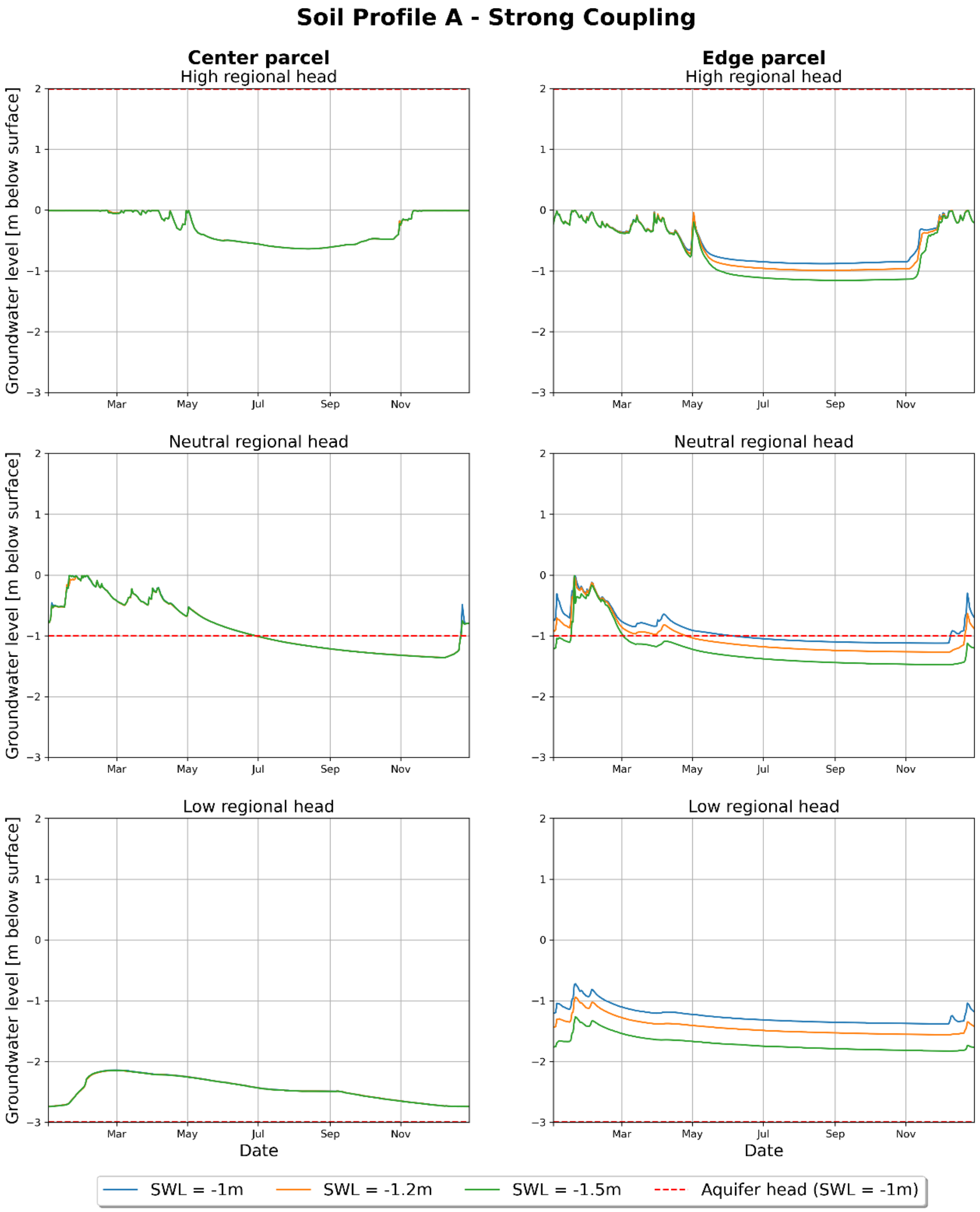

Soil Profile C - Weak Coupling
Center parcel
Edge parcel
High regional head
Neutral regional head
Low regional head
Groundwater level [m below surface]
2
1
0
−1
−2
−3
Mar
May
Jul
Sep
Nov
Date
SWL = -1m
SWL = -1.2m
SWL = -1.5m
Aquifer head (SWL = -1m)

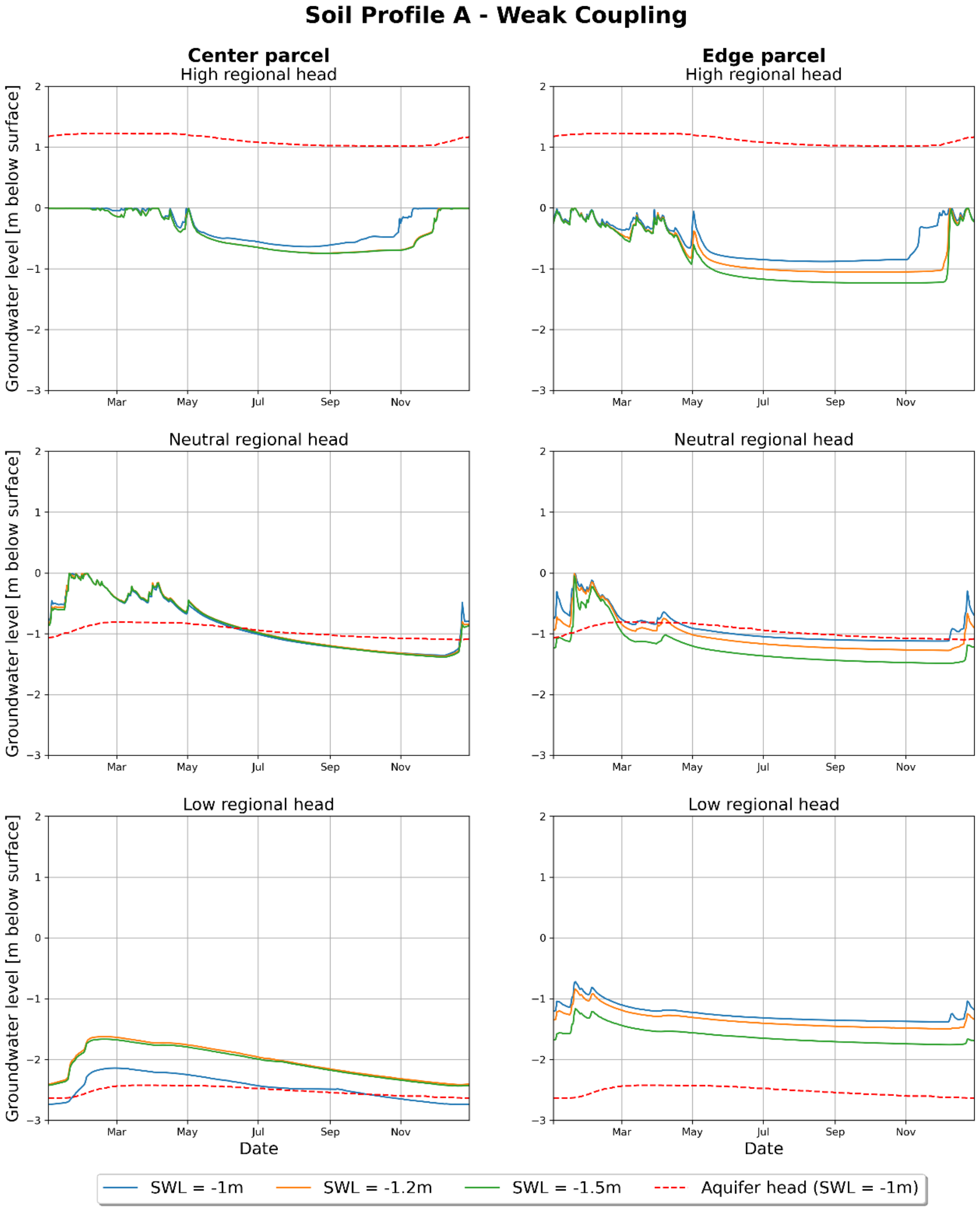

Soil Profile D - Strong Coupling
Center parcel
Edge parcel
High regional head
Neutral regional head
Low regional head
Groundwater level [m below surface]
2
1
0
−1
−2
−3
Mar
May
Jul
Sep
Nov
Date
SWL = -1m
SWL = -1.2m
SWL = -1.5m
Aquifer head (SWL = -1m)

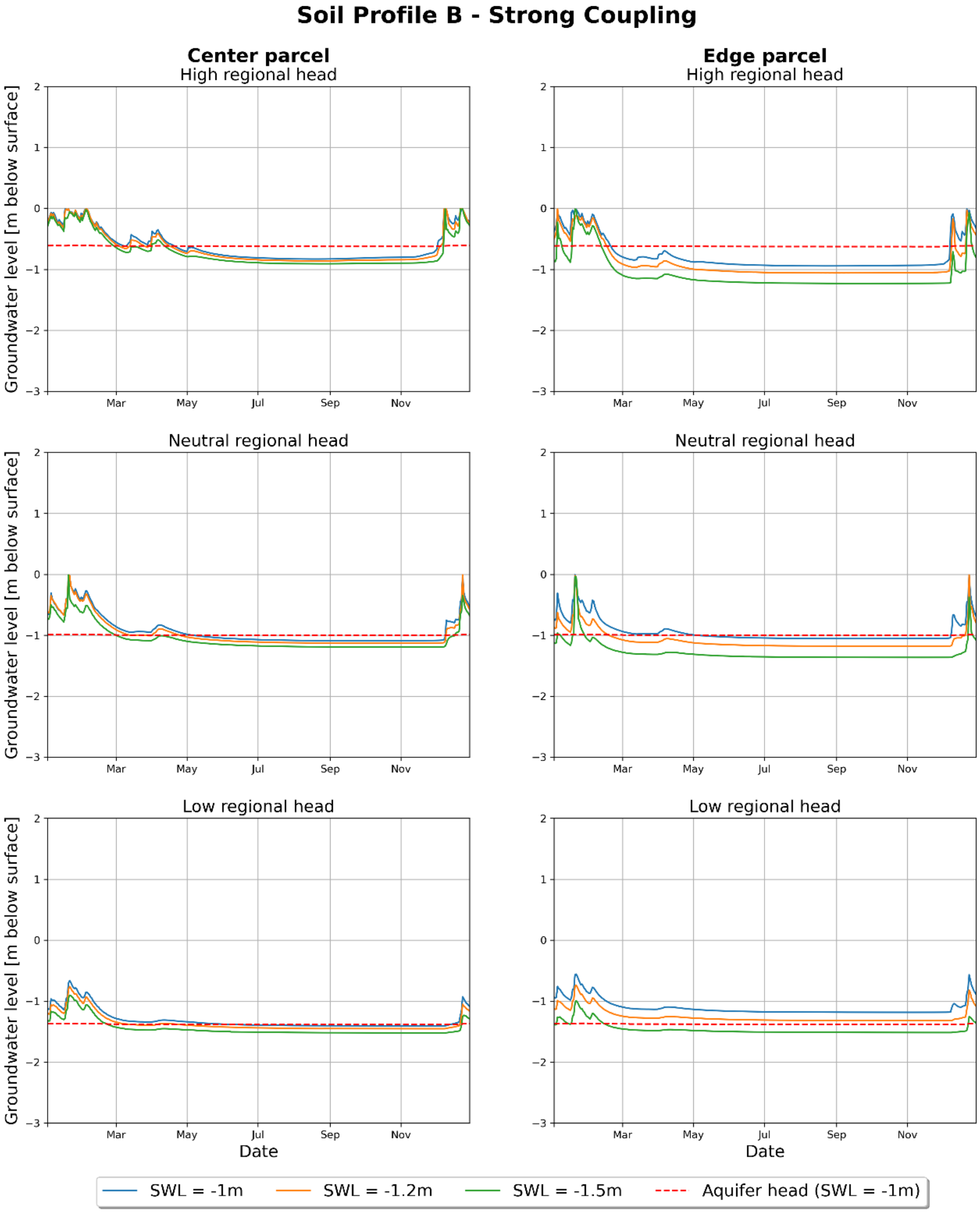

Soil Profile D - Weak Coupling
Center parcel
High regional head
Edge parcel
High regional head
Neutral regional head
Neutral regional head
Low regional head
Low regional head
Groundwater level [m below surface]
2
1
0
−1
−2
−3
Mar
May
Jul
Sep
Nov
Date
SWL = -1m
SWL = -1.2m
SWL = -1.5m
Aquifer head (SWL = -1m)

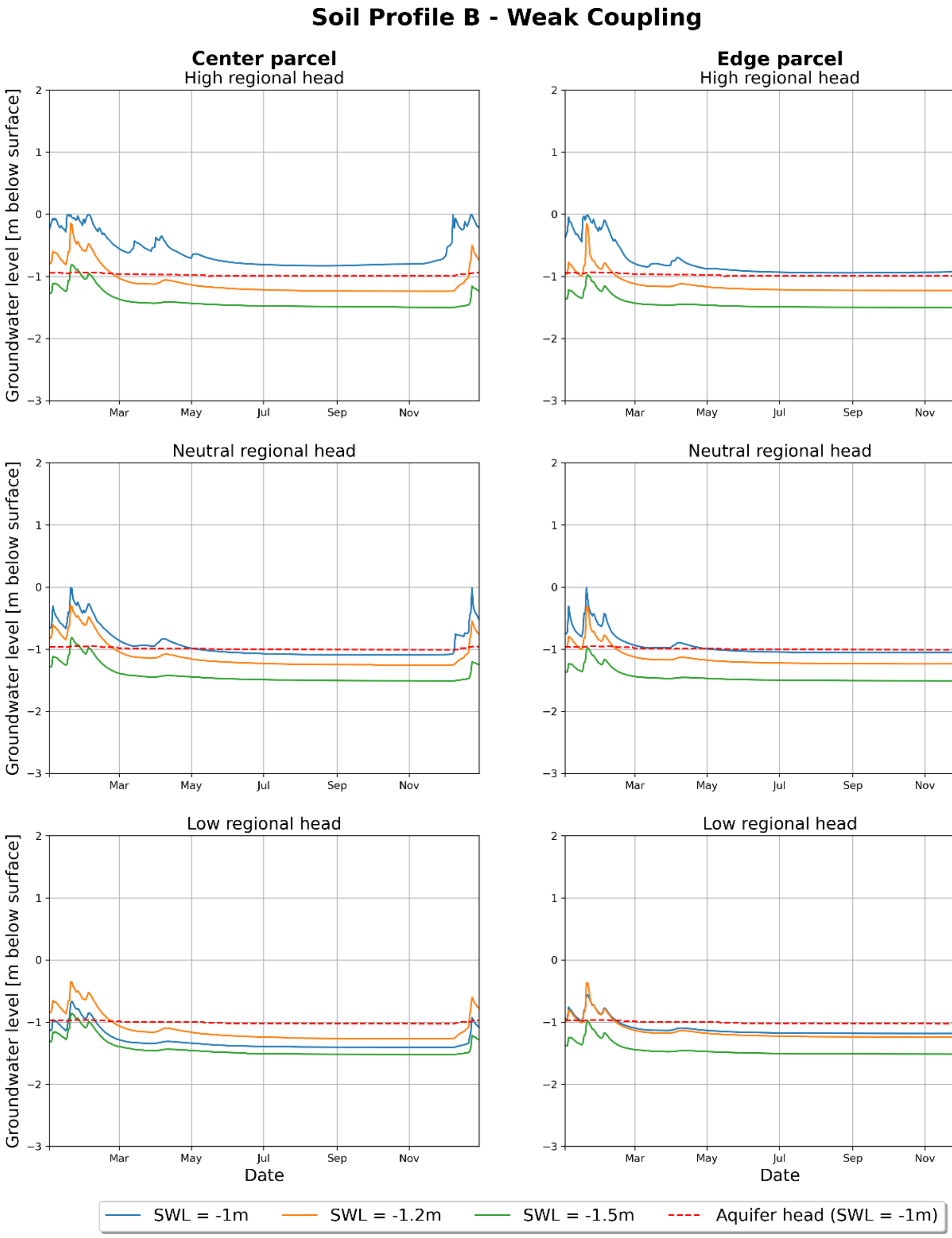
Appendix C3 Results (wider ditch) – GWT and hydraulic head time series

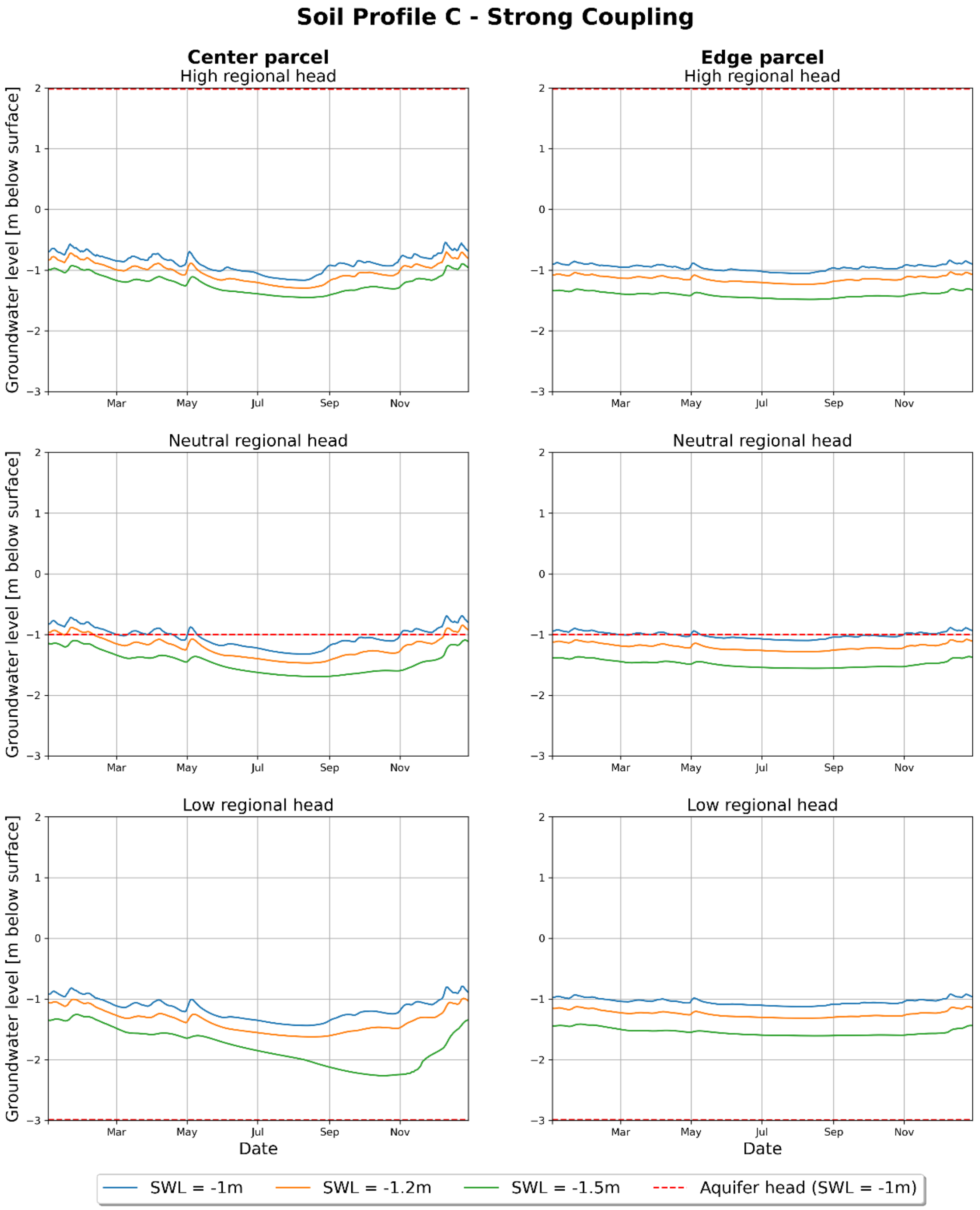
This appendix presents graphics of the GWT time series for the third year (2018). Left: centre of the parcel. Right: ‘edge’ of the parcel. The hydraulic head in the deep aquifer is depicted as well (only for the reference SWL). The difference between the aquifer head and GWT indicates if upward or downward seepage conditions prevail and the extent to which the aquifer head adjusts to the GWT changes (most apparent for weak coupling).

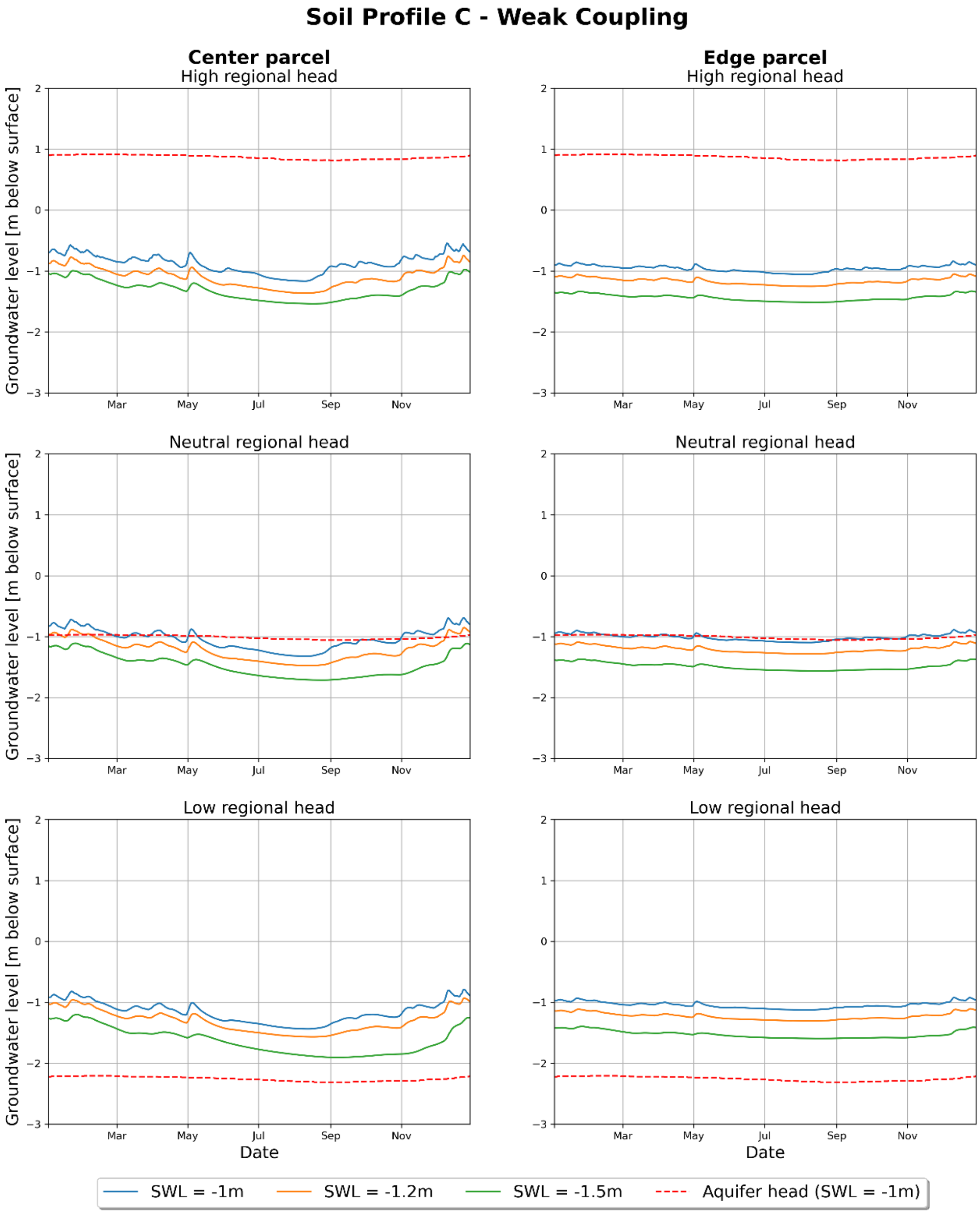


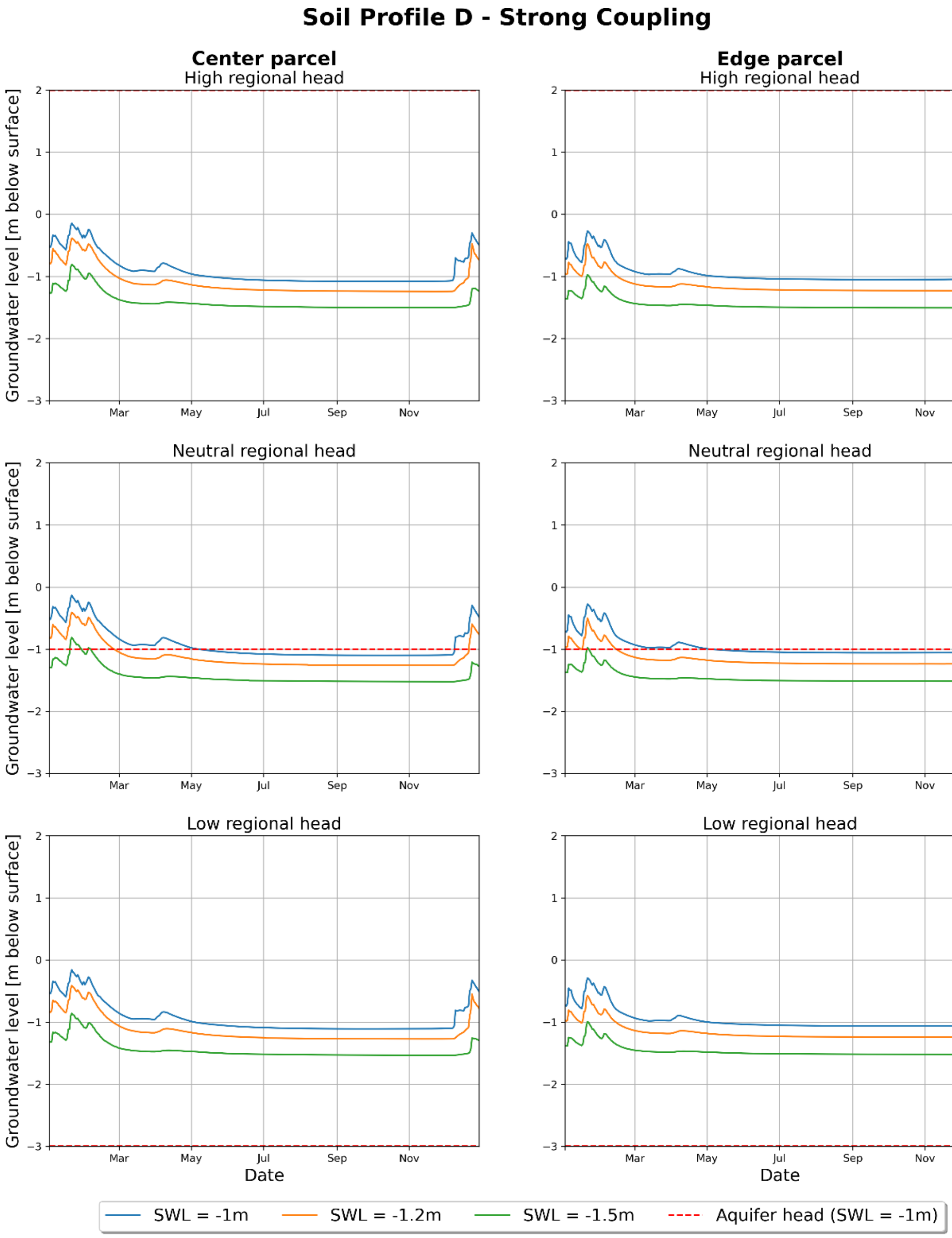

Soil Profile A - Weak Coupling
Center parcel
High regional head
Edge parcel
High regional head
Neutral regional head
Neutral regional head
Low regional head
Low regional head
Groundwater level [m below surface]
2
1
0
−1
−2
−3
Mar
May
Jul
Sep
Nov
Date
SWL = -1m
SWL = -1.2m
SWL = -1.5m
Aquifer head (SWL = -1m)

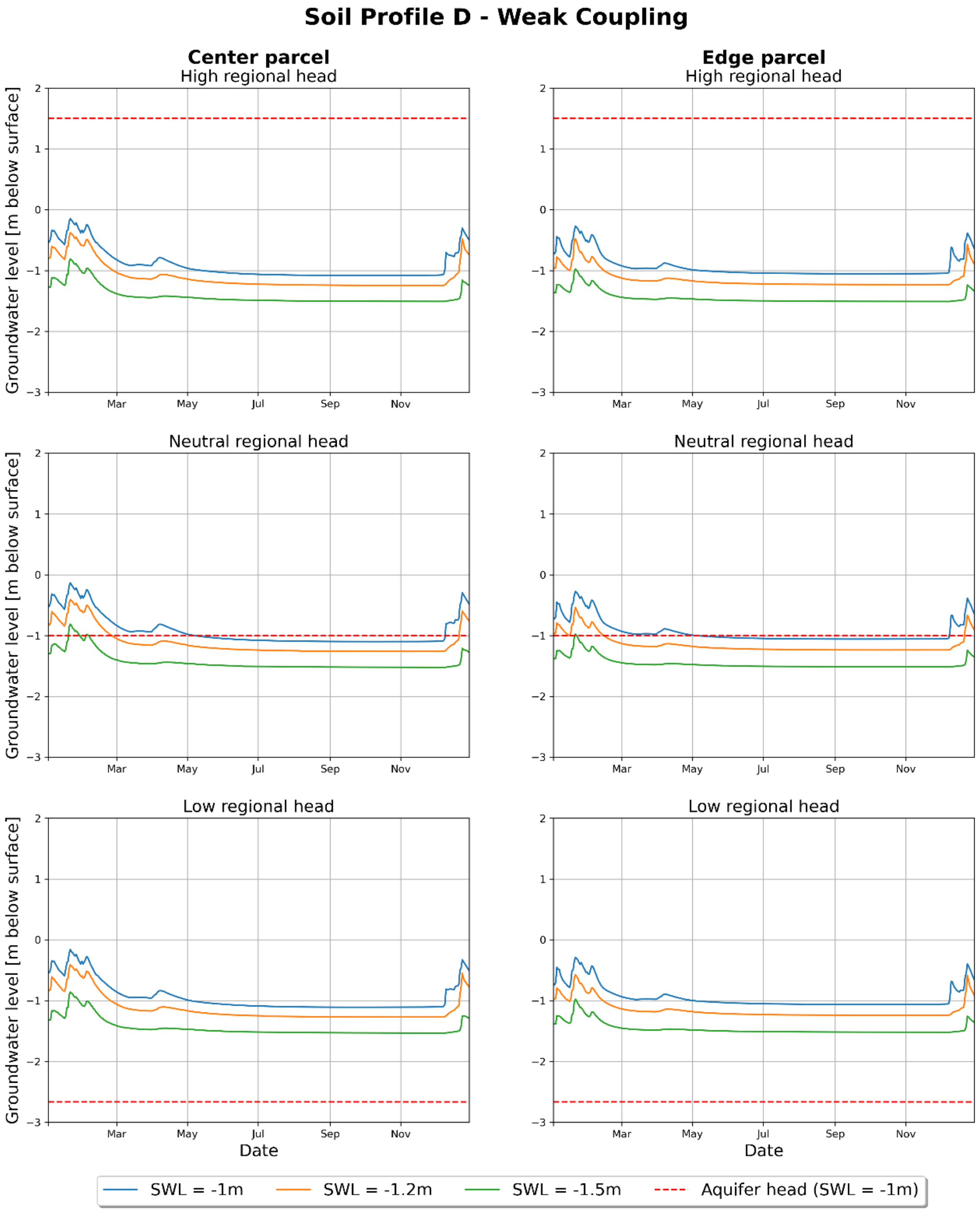

Soil Profile B - Strong Coupling
Center parcel
Edge parcel
High regional head
Neutral regional head
Low regional head
Groundwater level [m below surface]
2
1
0
−1
−2
−3
Mar
May
Jul
Sep
Nov
Date
SWL = -1m
SWL = -1.2m
SWL = -1.5m
Aquifer head (SWL = -1m)


Soil Profile B - Weak Coupling
Center parcel
Edge parcel
High regional head
Neutral regional head
Low regional head
Groundwater level [m below surface]
2
1
0
−1
−2
−3
Mar
May
Jul
Sep
Nov
Date
SWL = -1m
SWL = -1.2m
SWL = -1.5m
Aquifer head (SWL = -1m)


Soil Profile C - Strong Coupling
Center parcel
Edge parcel
High regional head
Neutral regional head
Low regional head
Groundwater level [m below surface]
2
1
0
−1
−2
−3
Mar
May
Jul
Sep
Nov
Date
SWL = -1m
SWL = -1.2m
SWL = -1.5m
Aquifer head (SWL = -1m)

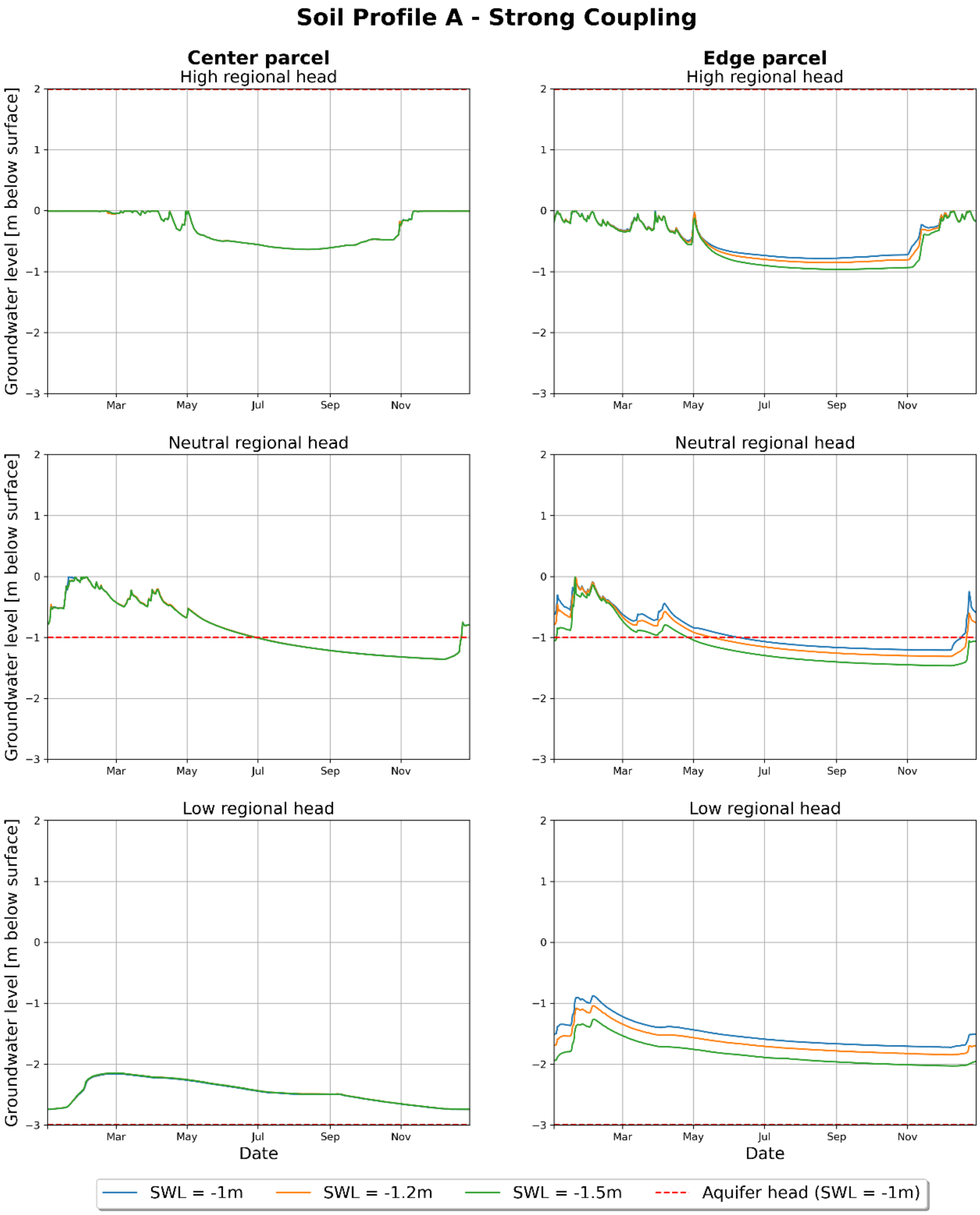

Soil Profile C - Weak Coupling
Center parcel
Edge parcel
High regional head
Neutral regional head
Low regional head
Groundwater level [m below surface]
2
1
0
−1
−2
−3
Mar
May
Jul
Sep
Nov
Date
SWL = -1m
SWL = -1.2m
SWL = -1.5m
Aquifer head (SWL = -1m)

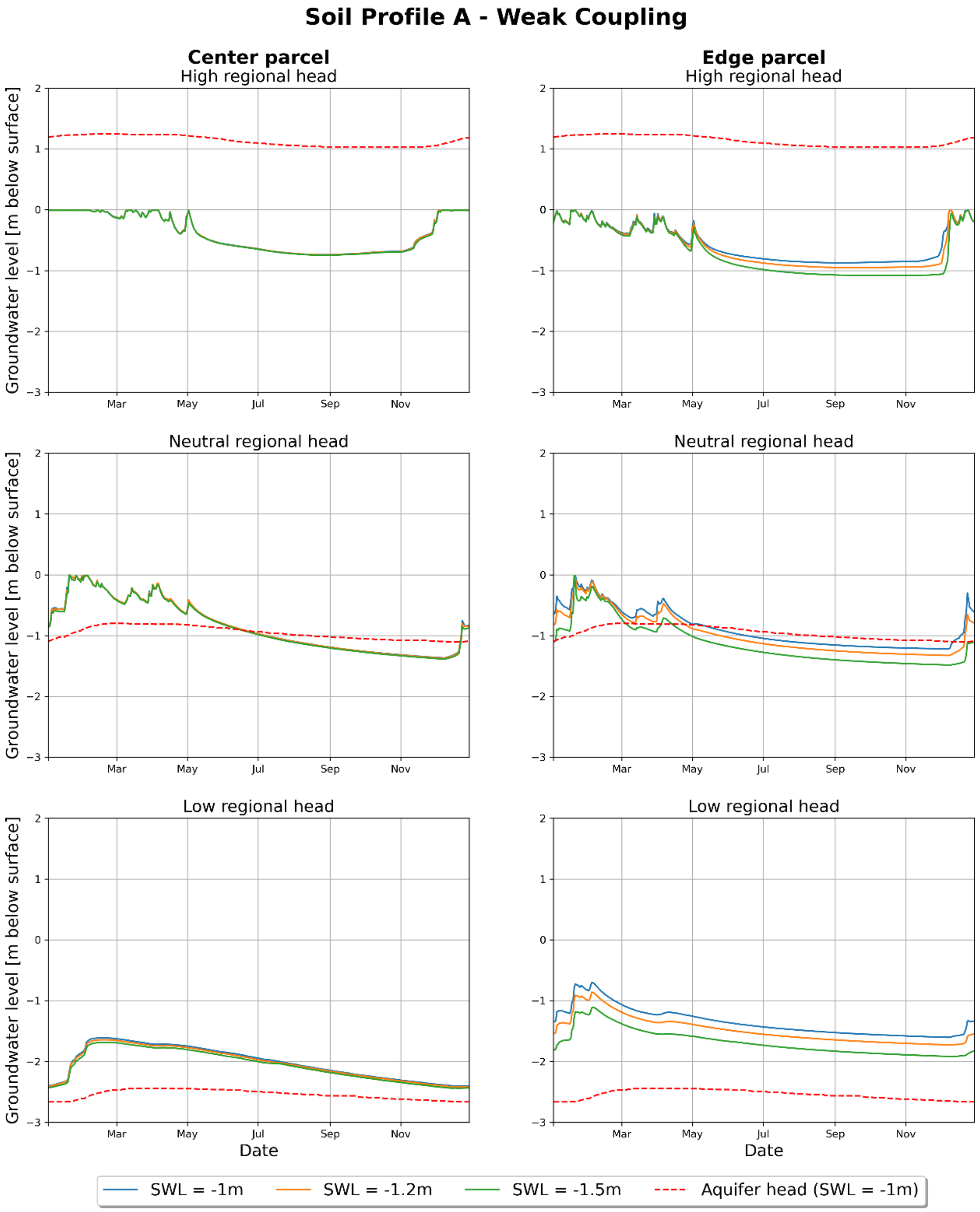

Soil Profile D - Strong Coupling
Center parcel
High regional head
Edge parcel
High regional head
Neutral regional head
Neutral regional head
Low regional head
Low regional head
Groundwater level [m below surface]
2
1
0
−1
−2
−3
Mar
May
Jul
Sep
Nov
Date
SWL = -1m
SWL = -1.2m
SWL = -1.5m
Aquifer head (SWL = -1m)

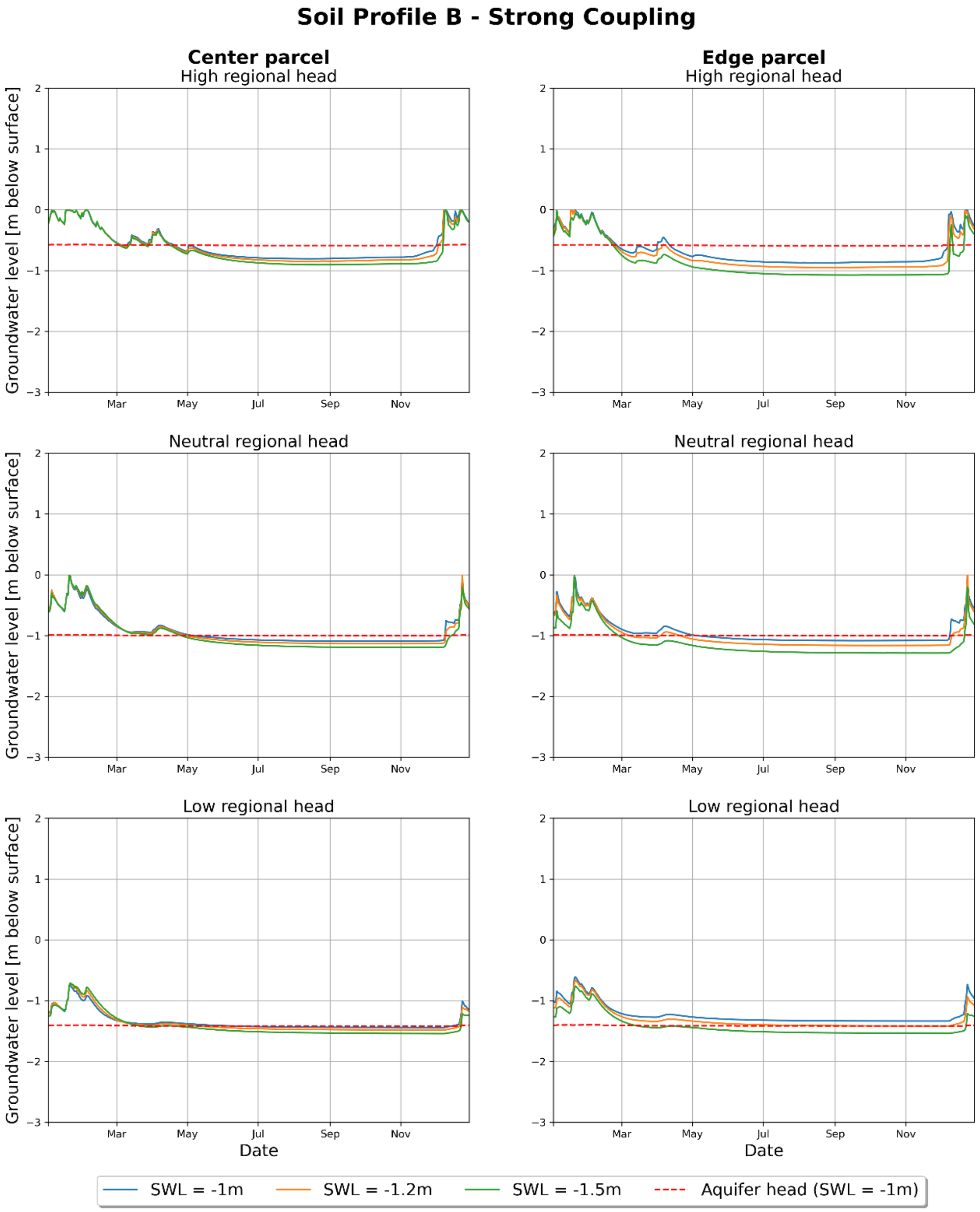

Soil Profile D - Weak Coupling
Center parcel
High regional head
Edge parcel
High regional head
Neutral regional head
Neutral regional head
Low regional head
Low regional head
Groundwater level [m below surface]
2
1
0
−1
−2
−3
Mar
May
Jul
Sep
Nov
Date
SWL = -1m
SWL = -1.2m
SWL = -1.5m
Aquifer head (SWL = -1m)

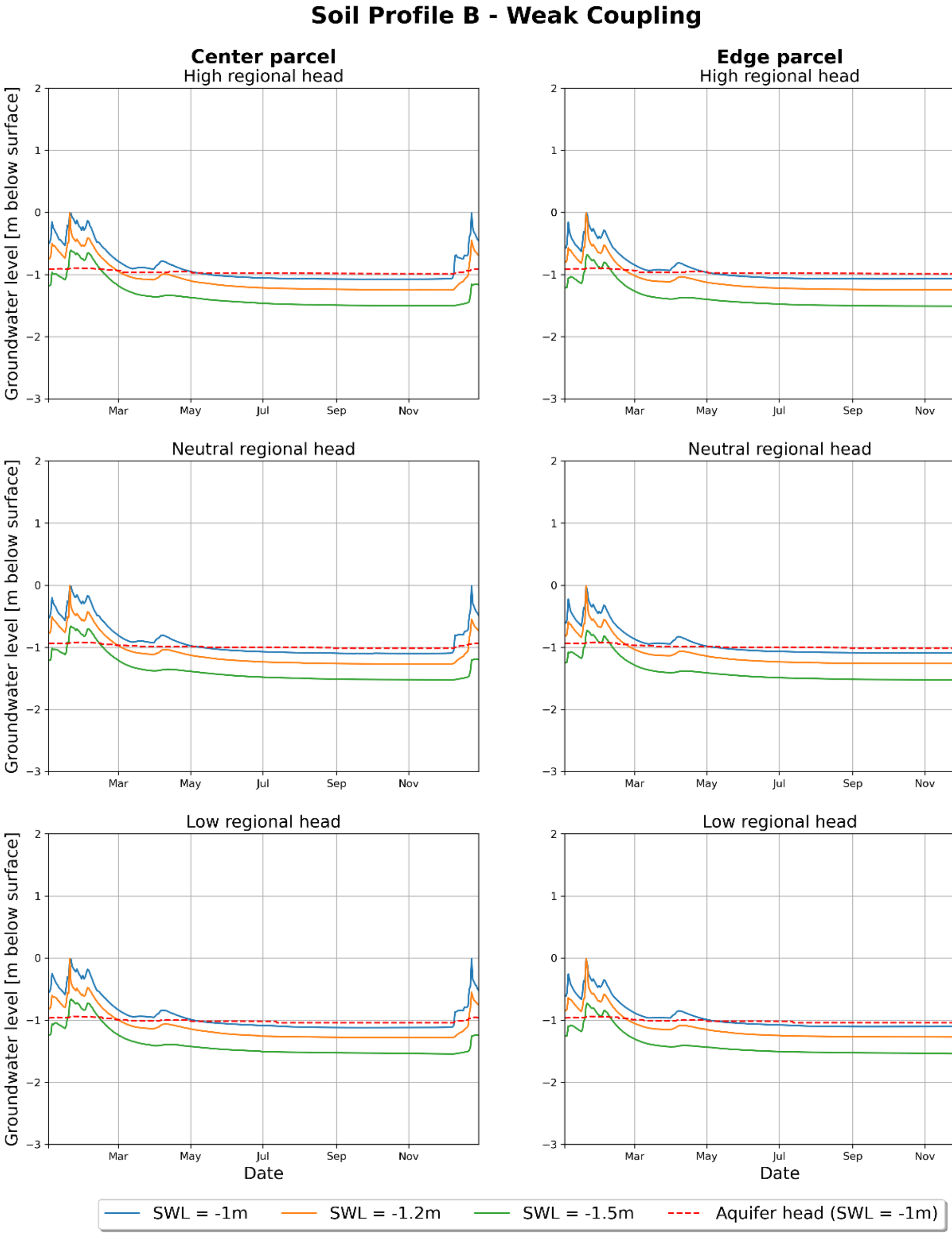
Appendix C4 Results (deepend ditch) – GWT and hydraulic head time series

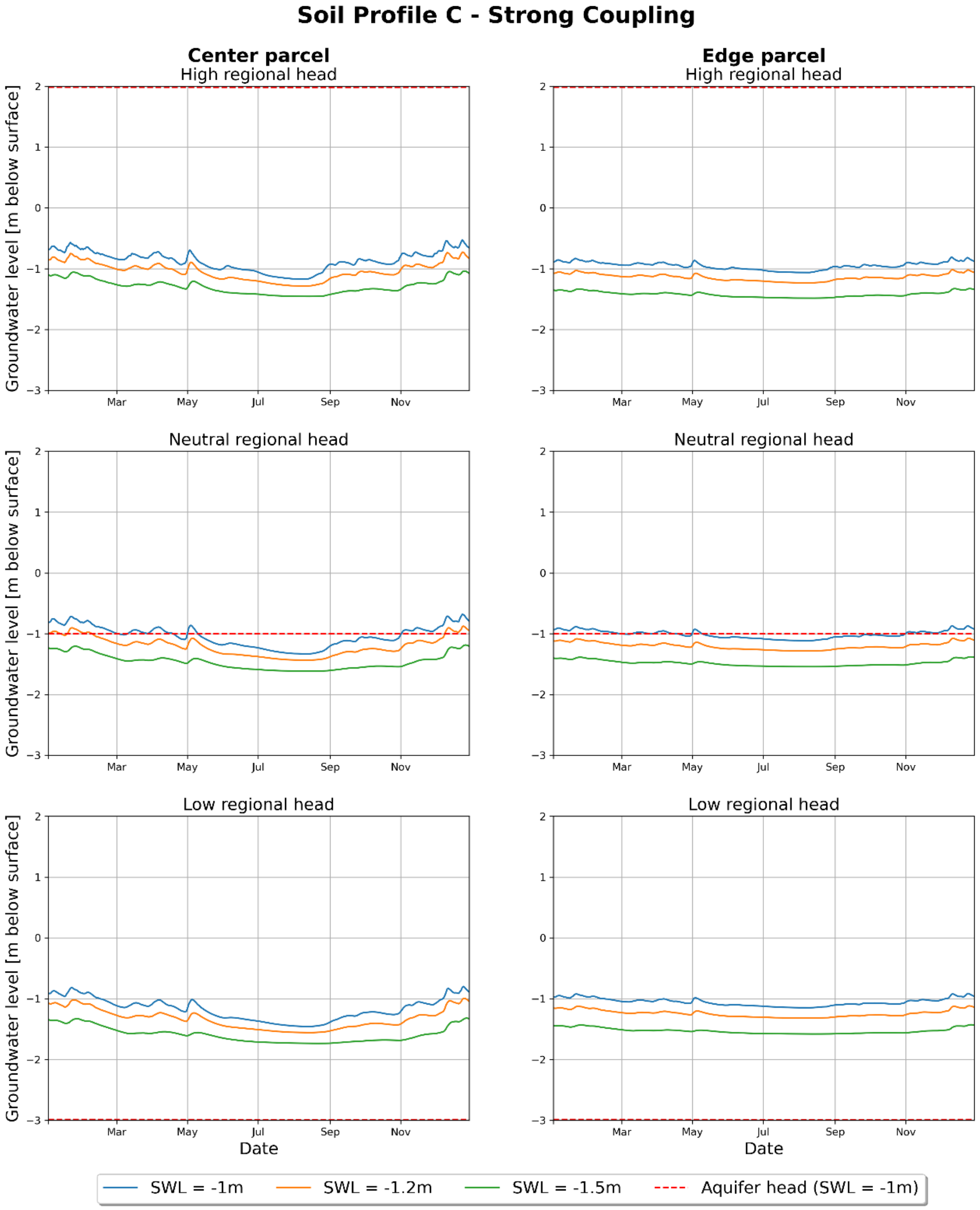
This appendix presents graphics of the GWT time series for the third year (2018). Left: centre of the parcel. Right: ‘edge’ of the parcel. The hydraulic head in the deep aquifer is depicted as well (only for the reference SWL). The difference between the aquifer head and GWT indicates if upward or downward seepage conditions prevail and the extent to which the aquifer head adjusts to the GWT changes (most apparent for weak coupling).

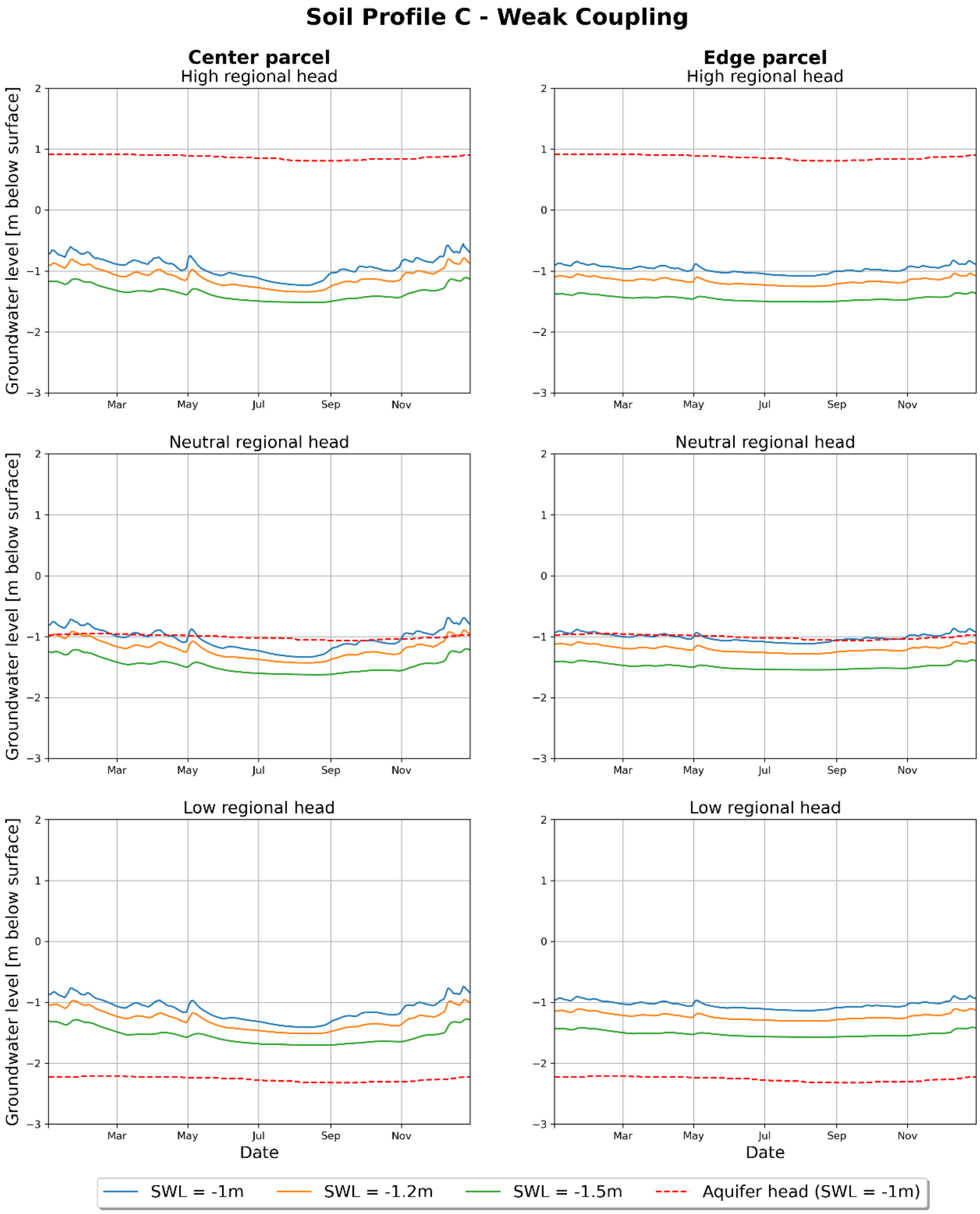


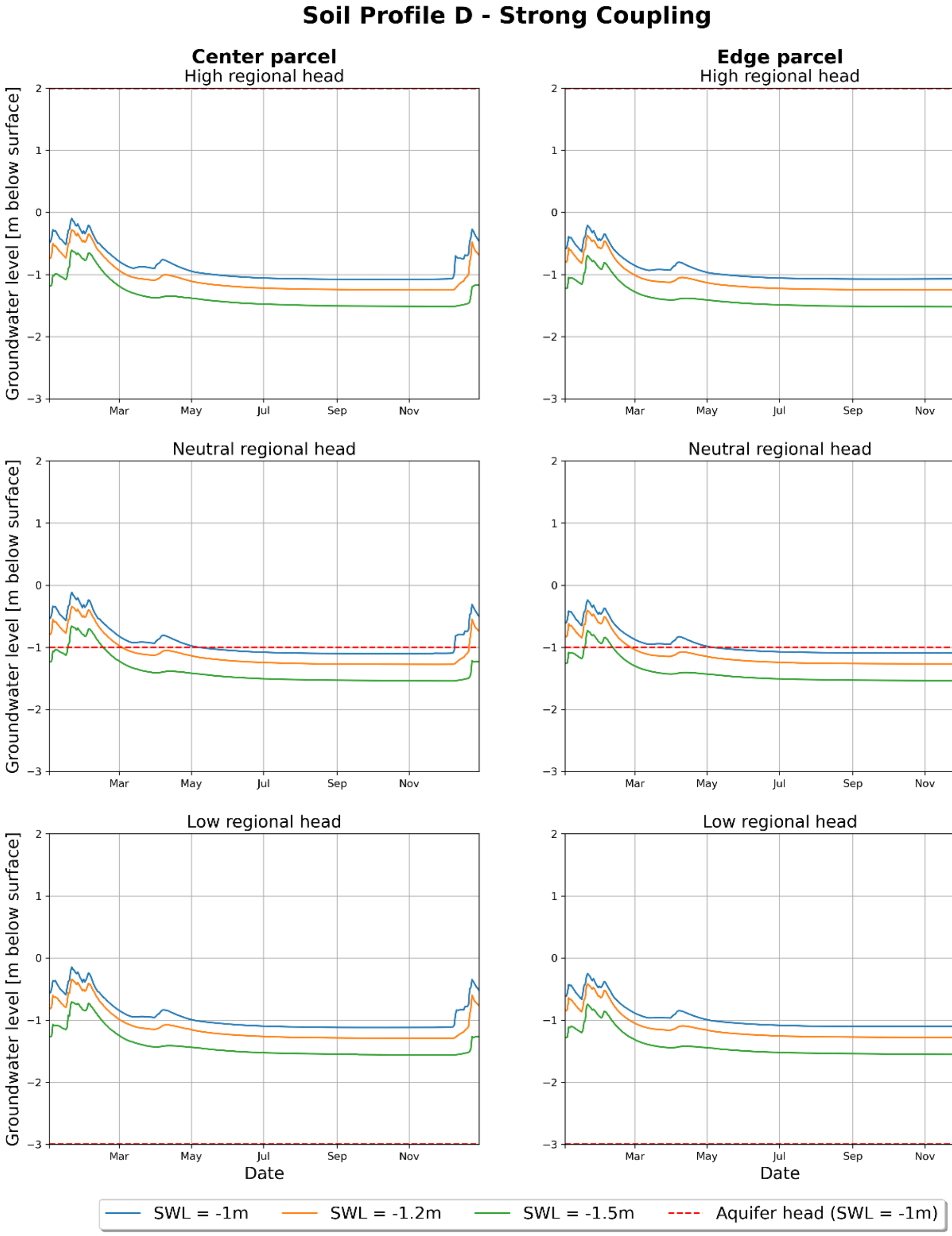

Soil Profile A - Weak Coupling
Center parcel
High regional head
Edge parcel
High regional head
Neutral regional head
Neutral regional head
Low regional head
Low regional head
Groundwater level [m below surface]
2
1
0
−1
−2
−3
Mar
May
Jul
Sep
Nov
Date
Date
SWL = -1m
SWL = -1.2m
SWL = -1.5m
Aquifer head (SWL = -1m)

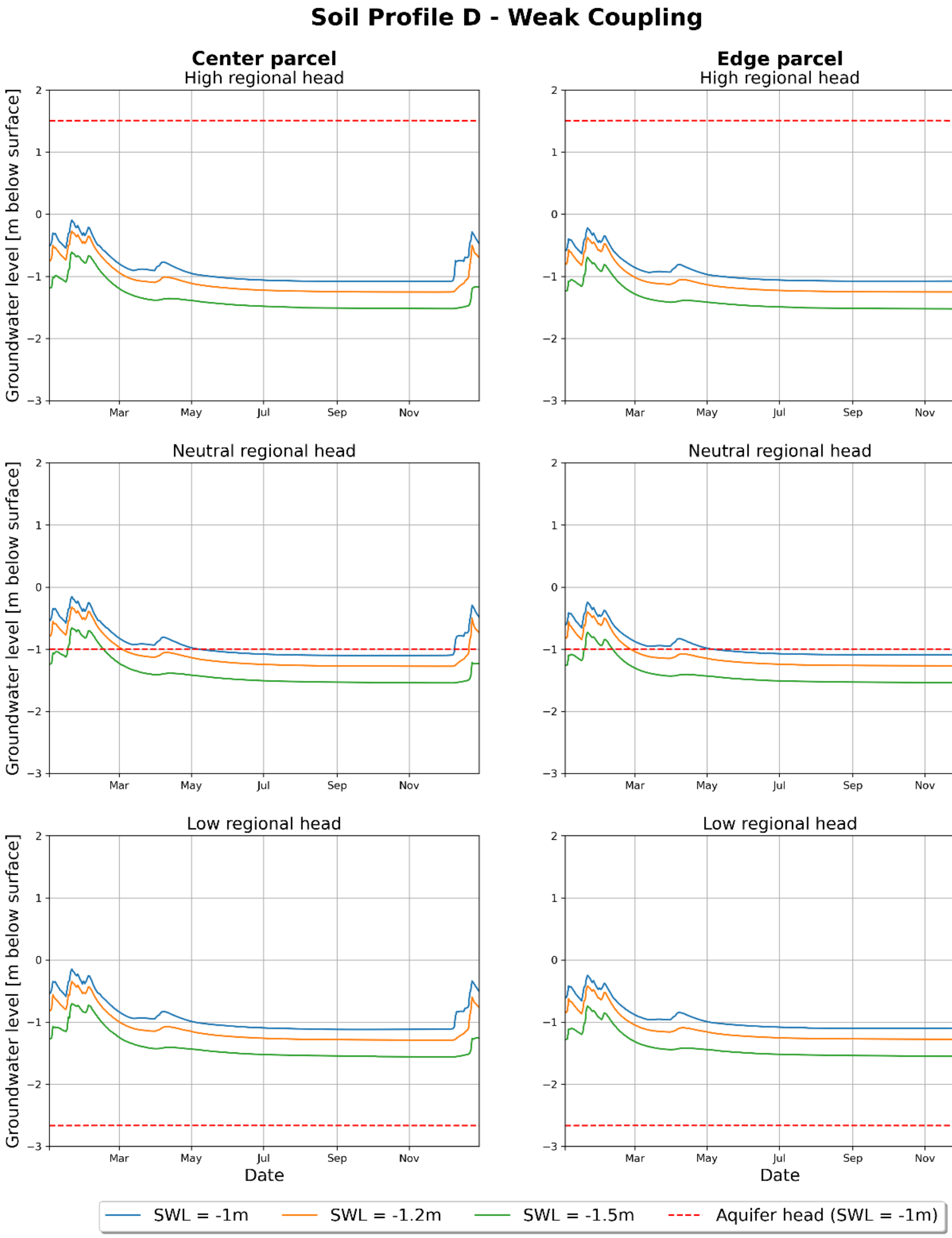

Soil Profile B - Strong Coupling
Center parcel
High regional head
Edge parcel
High regional head
Neutral regional head
Neutral regional head
Low regional head
Low regional head
Groundwater level [m below surface]
2
1
0
−1
−2
−3
Mar
May
Jul
Sep
Nov
Date
SWL = -1m
SWL = -1.2m
SWL = -1.5m
Aquifer head (SWL = -1m)


Soil Profile B - Weak Coupling
Center parcel
High regional head
Edge parcel
High regional head
Neutral regional head
Neutral regional head
Low regional head
Low regional head
Groundwater level [m below surface]
2
1
0
−1
−2
−3
Mar
May
Jul
Sep
Nov
Date
SWL = -1m
SWL = -1.2m
SWL = -1.5m
Aquifer head (SWL = -1m)


Soil Profile C - Strong Coupling
Center parcel
Edge parcel
High regional head
Neutral regional head
Low regional head
Groundwater level [m below surface]
2
1
0
−1
−2
−3
Mar
May
Jul
Sep
Nov
Date
SWL = -1m
SWL = -1.2m
SWL = -1.5m
Aquifer head (SWL = -1m)

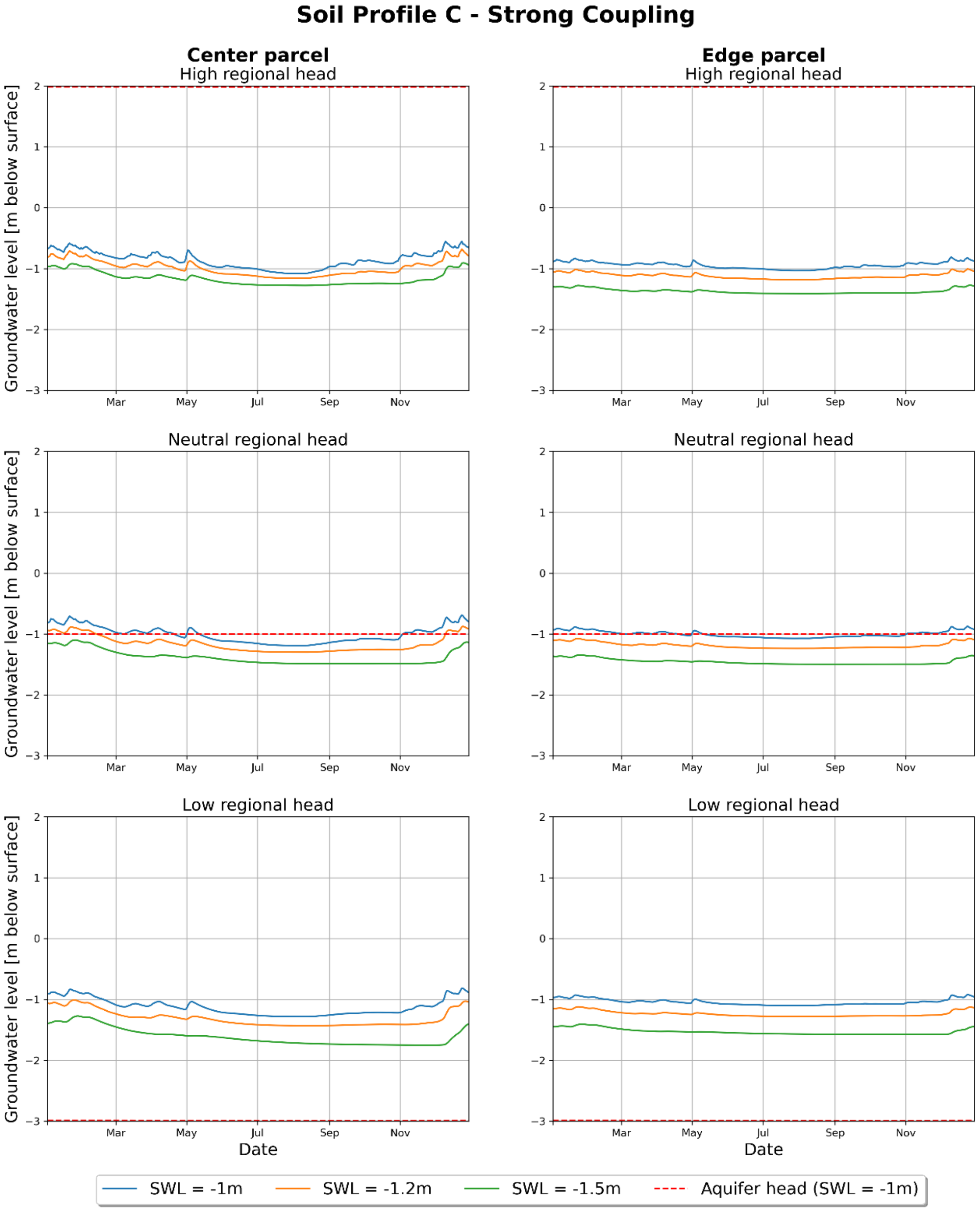

Soil Profile C - Weak Coupling
Center parcel
High regional head
Edge parcel
High regional head
Neutral regional head
Neutral regional head
Low regional head
Low regional head
Groundwater level [m below surface]
2
1
0
−1
−2
−3
Mar
May
Jul
Sep
Nov
Date
SWL = -1m
SWL = -1.2m
SWL = -1.5m
Aquifer head (SWL = -1m)

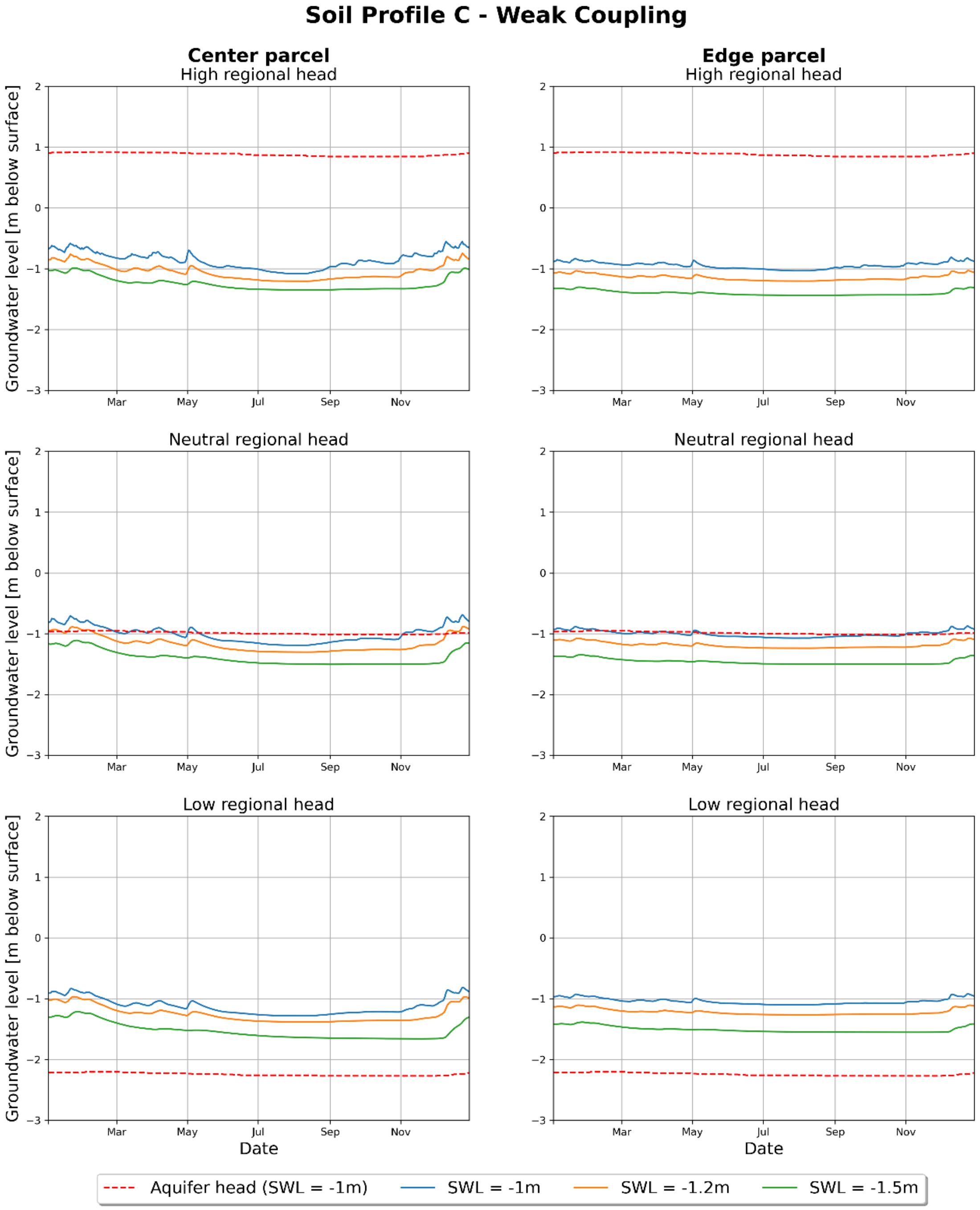

Soil Profile D - Strong Coupling
Center parcel
Edge parcel
High regional head
Neutral regional head
Low regional head
Groundwater level [m below surface]
2
1
0
−1
−2
−3
Mar
May
Jul
Sep
Nov
Date
SWL = -1m
SWL = -1.2m
SWL = -1.5m
Aquifer head (SWL = -1m)


Soil Profile D - Weak Coupling
Center parcel
High regional head
Edge parcel
High regional head
Neutral regional head
Neutral regional head
Low regional head
Low regional head
Groundwater level [m below surface]
2
1
0
−1
−2
−3
Mar
May
Jul
Sep
Nov
Date
SWL = -1m
SWL = -1.2m
SWL = -1.5m
Aquifer head (SWL = -1m)

Appendix C5 Results (different top soil sand) – GWT and hydraulic head time series

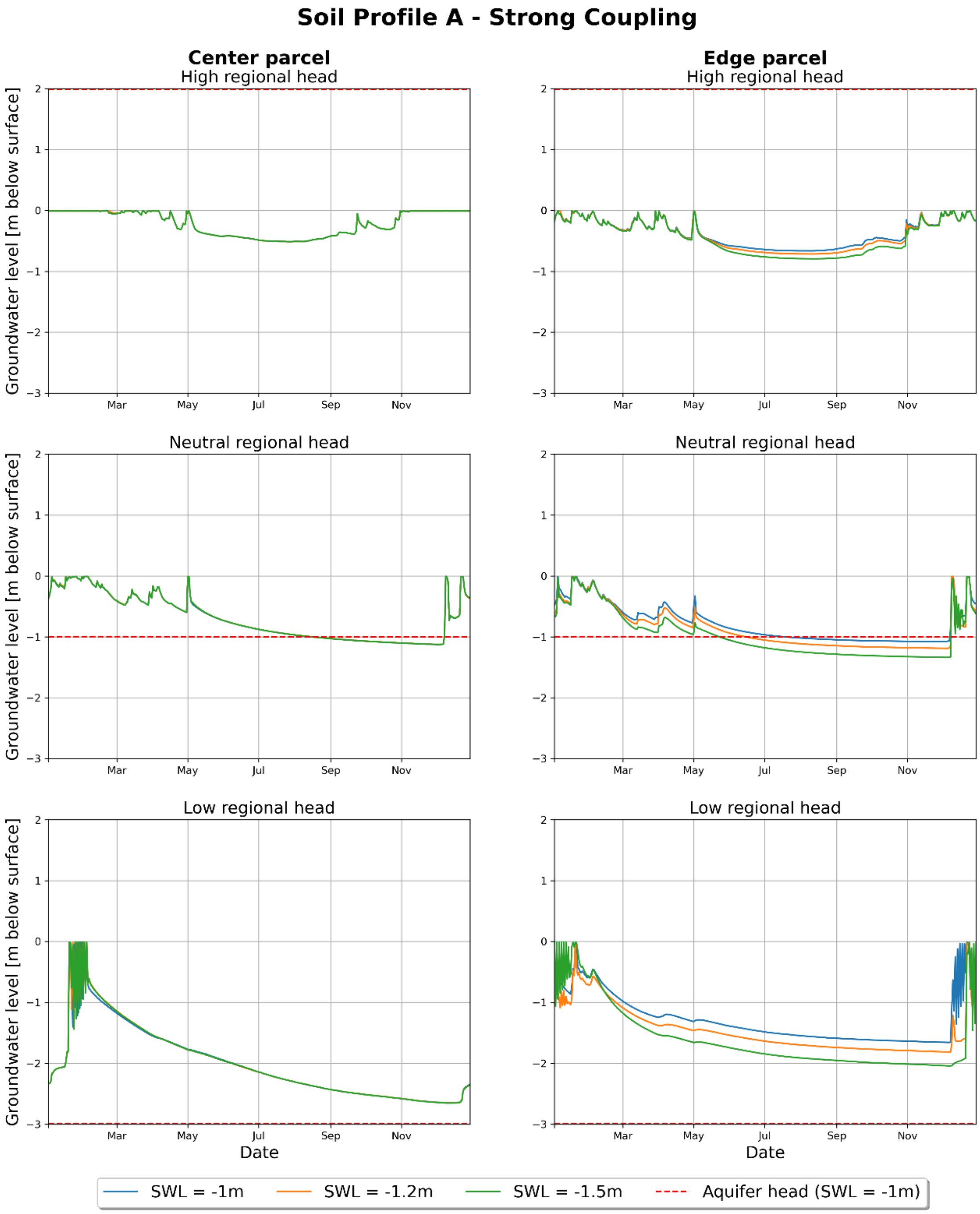
This appendix presents graphics of the GWT time series for the third year (2018). Left: centre of the parcel. Right: ‘edge’ of the parcel. The hydraulic head in the deep aquifer is depicted as well (only for the reference SWL). The difference between the aquifer head and GWT indicates if upward or downward seepage conditions prevail and the extent to which the aquifer head adjusts to the GWT changes (most apparent for weak coupling).

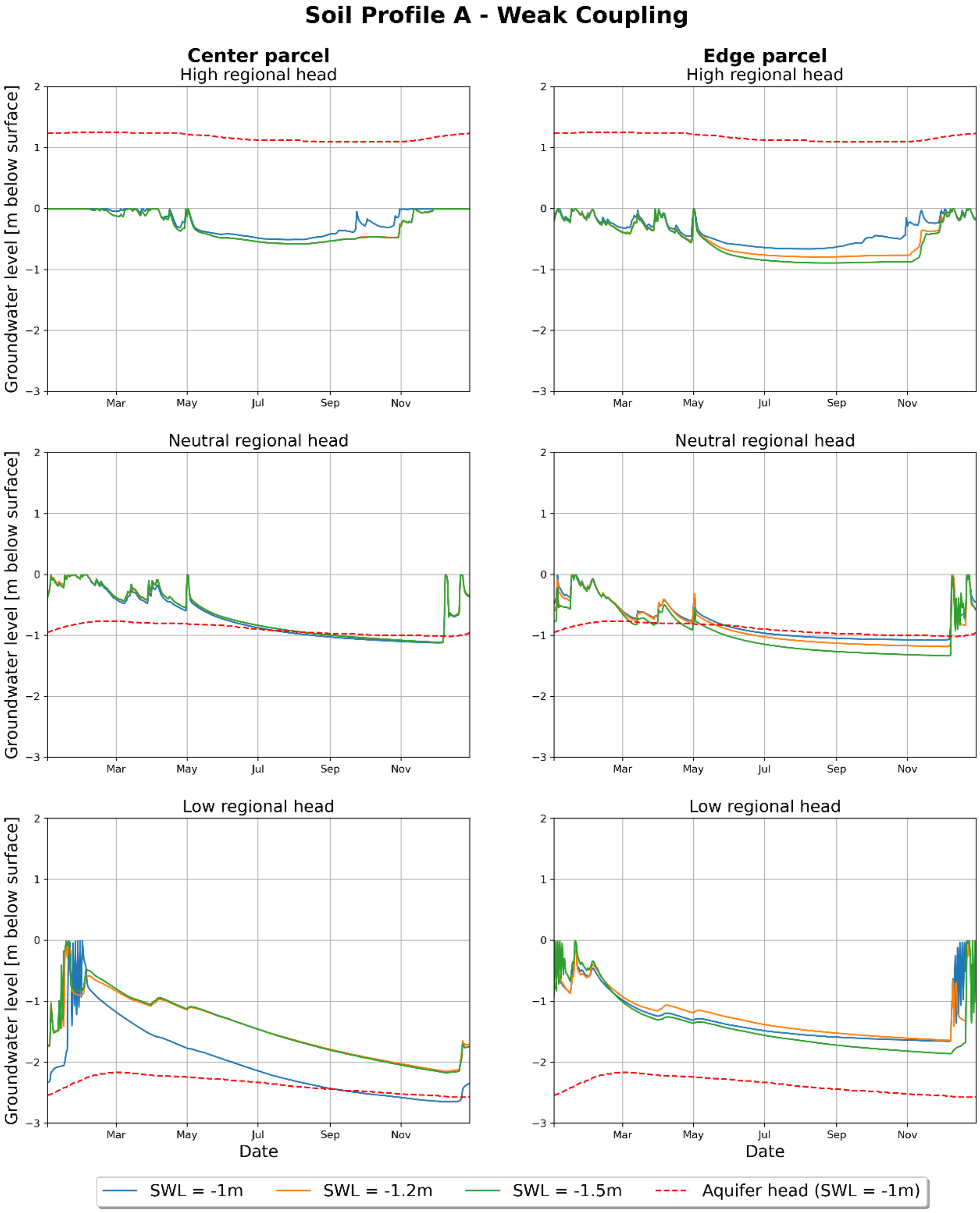


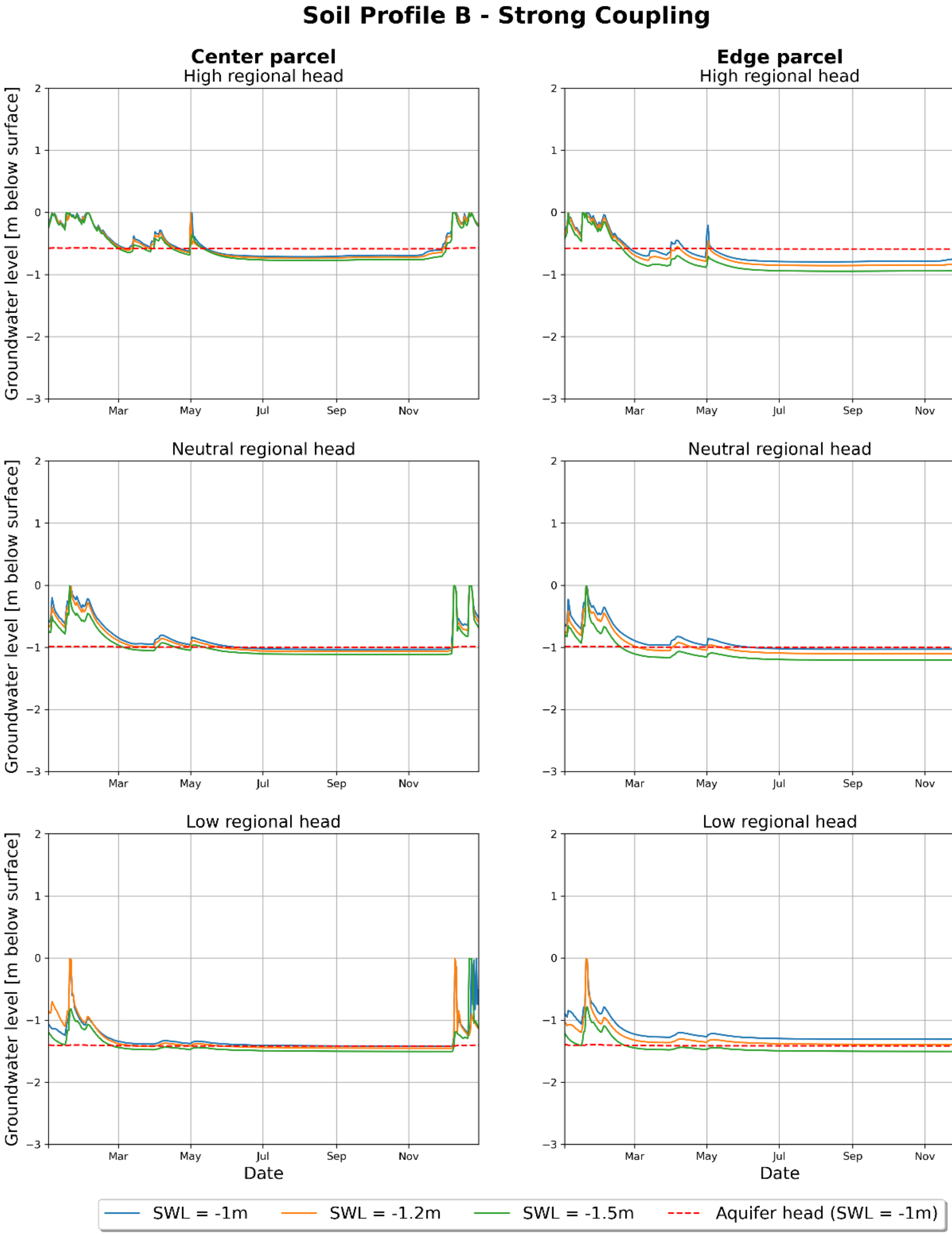

Soil Profile C - Weak Coupling
Center parcel
Edge parcel
High regional head
Neutral regional head
Low regional head
Groundwater level [m below surface]
2
1
0
−1
−2
−3
Mar
May
Jul
Sep
Nov
Date
Aquifer head (SWL = -1m)
SWL = -1m
SWL = -1.2m
SWL = -1.5m

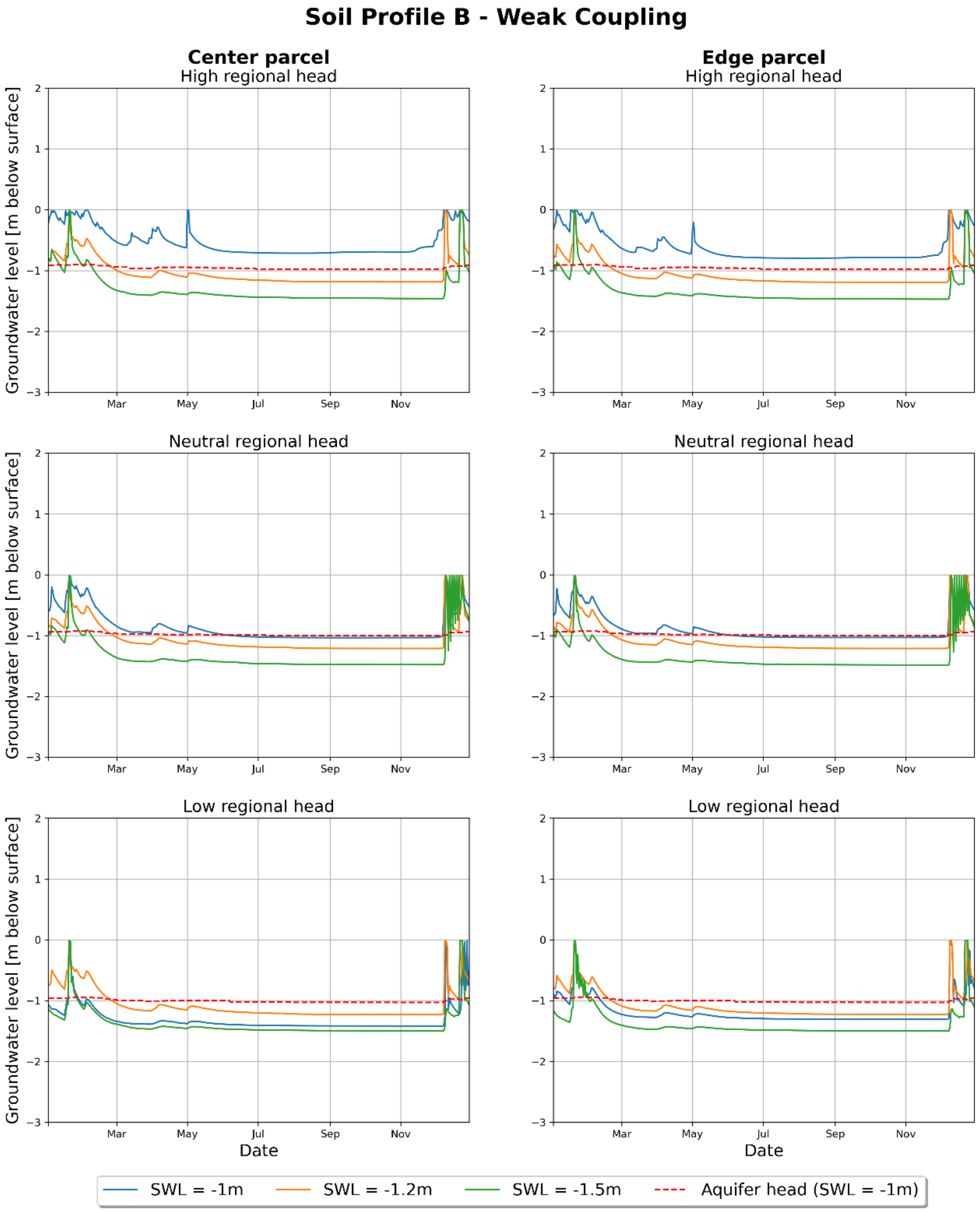
Appendix C6 Results (different clay type) – GWT and hydraulic head time series

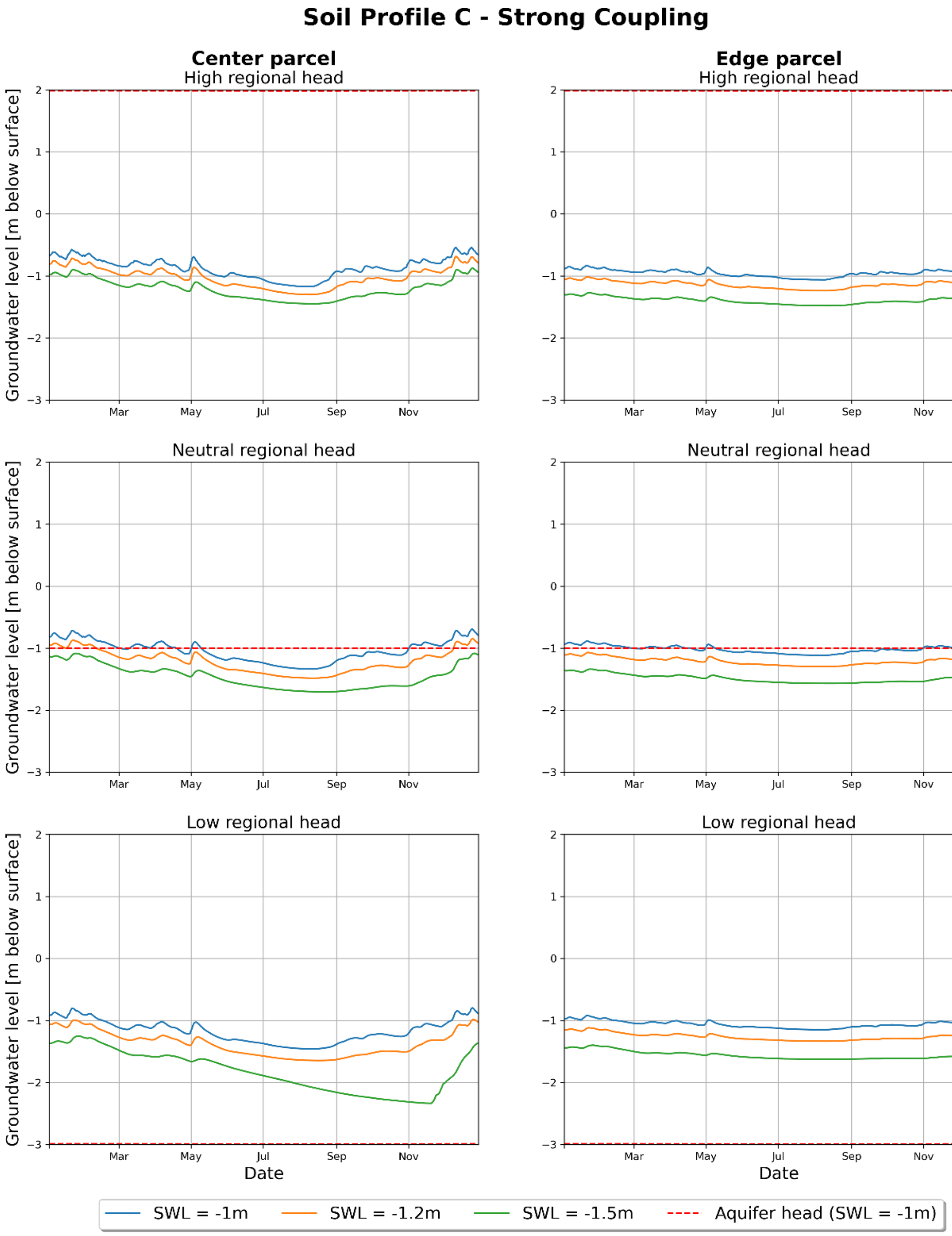
This appendix presents graphics of the GWT time series for the third year (2018). Left: centre of the parcel. Right: ‘edge’ of the parcel. The hydraulic head in the deep aquifer is depicted as well (only for the reference SWL). The difference between the aquifer head and GWT indicates if upward or downward seepage conditions prevail and the extent to which the aquifer head adjusts to the GWT changes (most apparent for weak coupling).

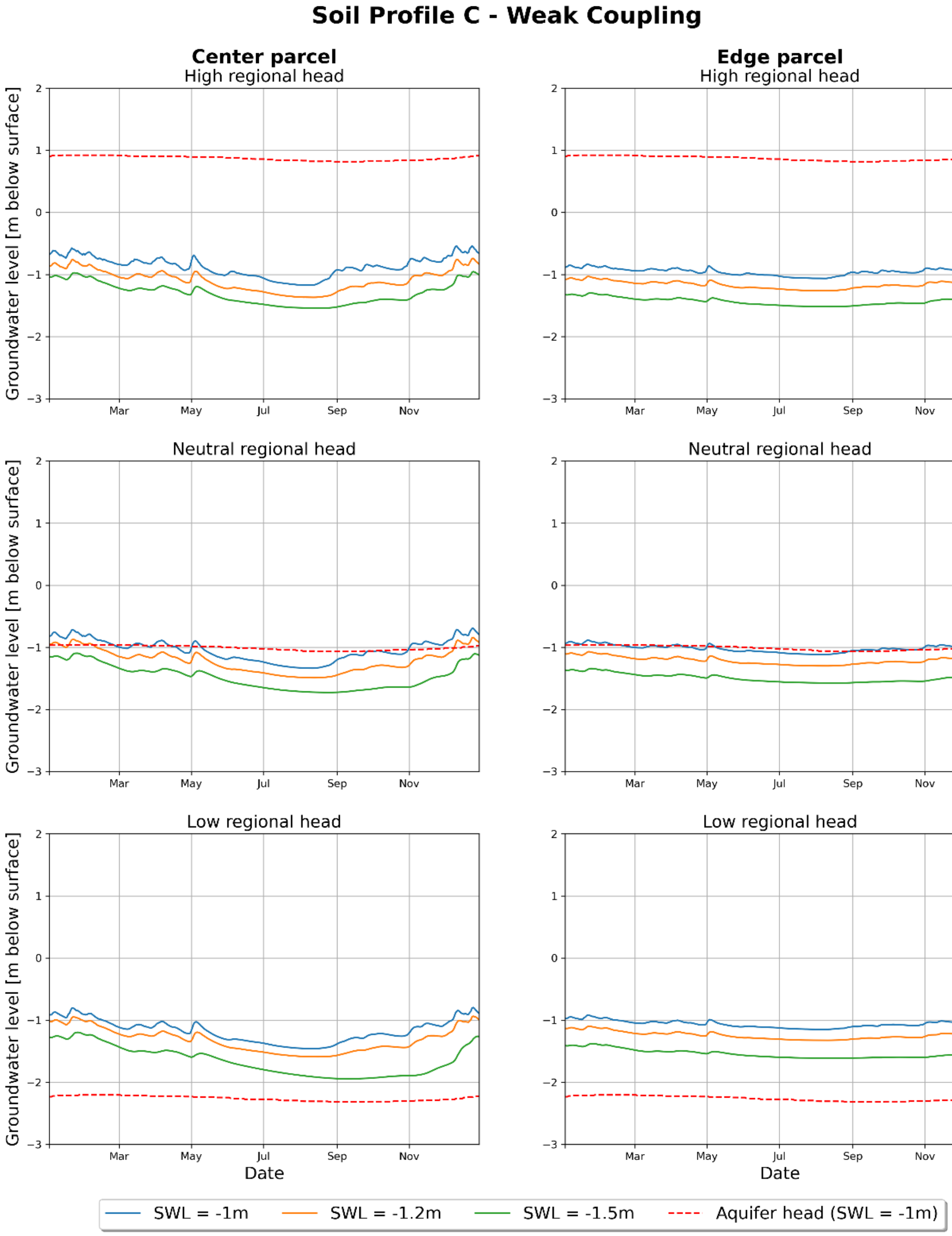


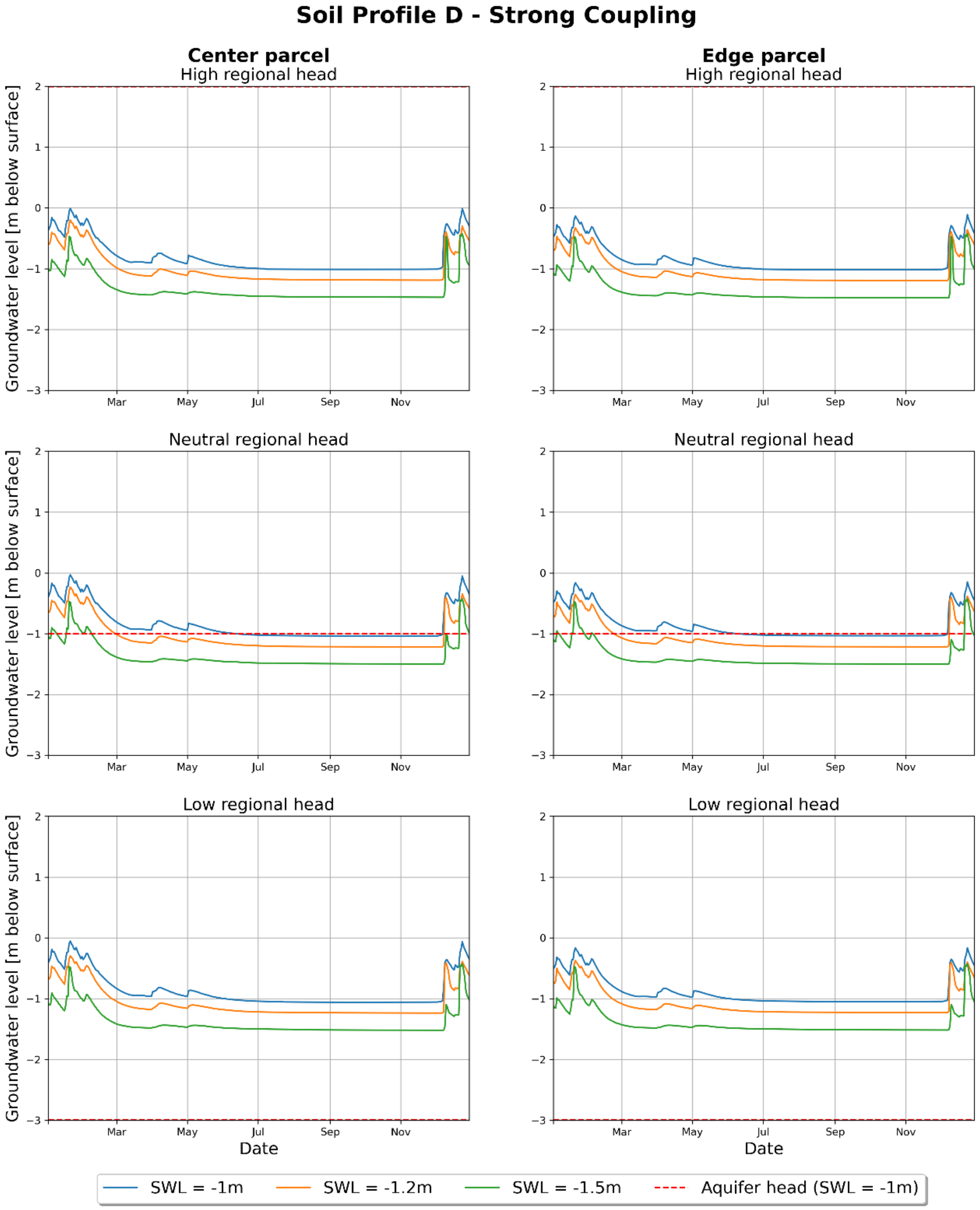

Soil Profile A - Weak Coupling
Center parcel
Edge parcel
High regional head
Neutral regional head
Low regional head
Groundwater level [m below surface]
2
1
0
−1
−2
−3
Mar
May
Jul
Sep
Nov
Date
SWL = -1m
SWL = -1.2m
SWL = -1.5m
Aquifer head (SWL = -1m)

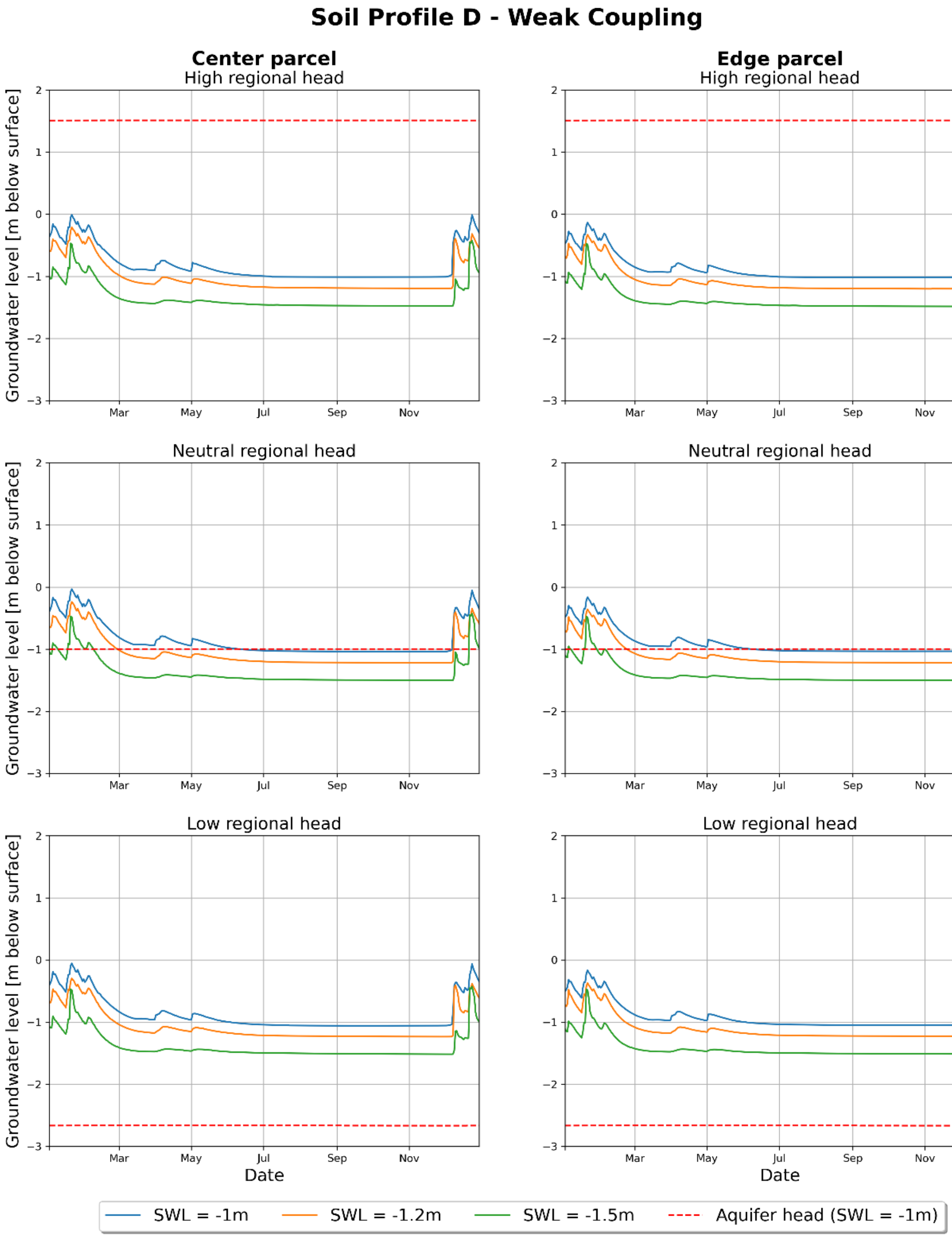

Soil Profile B - Strong Coupling
Center parcel
Edge parcel
High regional head
Neutral regional head
Low regional head
Groundwater level [m below surface]
2
1
0
−1
−2
−3
Mar
May
Jul
Sep
Nov
Date
SWL = -1m
SWL = -1.2m
SWL = -1.5m
Aquifer head (SWL = -1m)


Soil Profile B - Weak Coupling
Center parcel
Edge parcel
High regional head
Neutral regional head
Low regional head
Groundwater level [m below surface]
2
1
0
−1
−2
−3
Mar
May
Jul
Sep
Nov
Date
SWL = -1m
SWL = -1.2m
SWL = -1.5m
Aquifer head (SWL = -1m)


Soil Profile C - Strong Coupling
Center parcel
Edge parcel
High regional head
Neutral regional head
Low regional head
Groundwater level [m below surface]
2
1
0
−1
−2
−3
Mar
May
Jul
Sep
Nov
Date
SWL = -1m
SWL = -1.2m
SWL = -1.5m
Aquifer head (SWL = -1m)

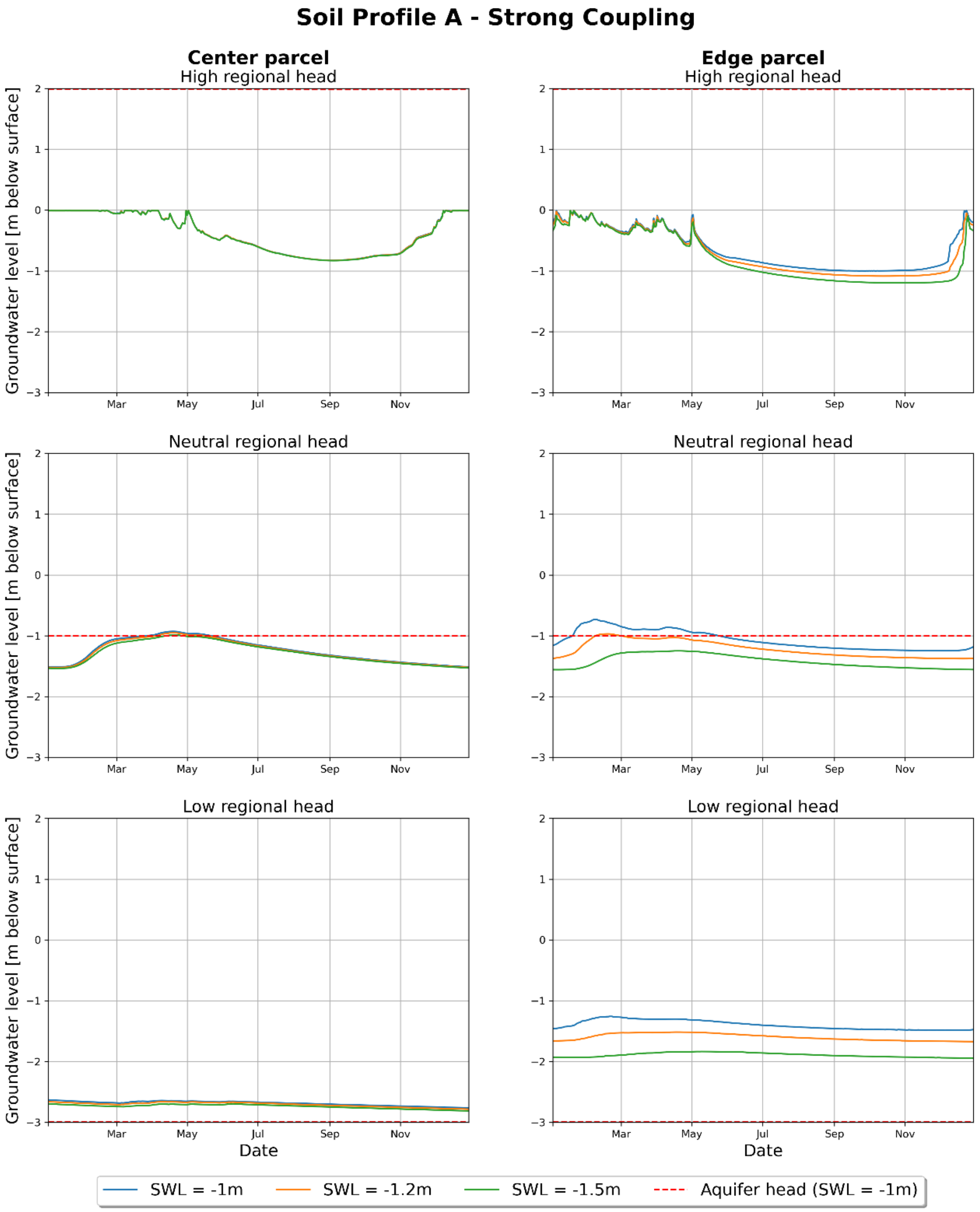

Soil Profile C - Weak Coupling
Center parcel
Edge parcel
High regional head
Neutral regional head
Low regional head
Groundwater level [m below surface]
2
1
0
−1
−2
−3
Mar
May
Jul
Sep
Nov
Date
SWL = -1m
SWL = -1.2m
SWL = -1.5m
Aquifer head (SWL = -1m)

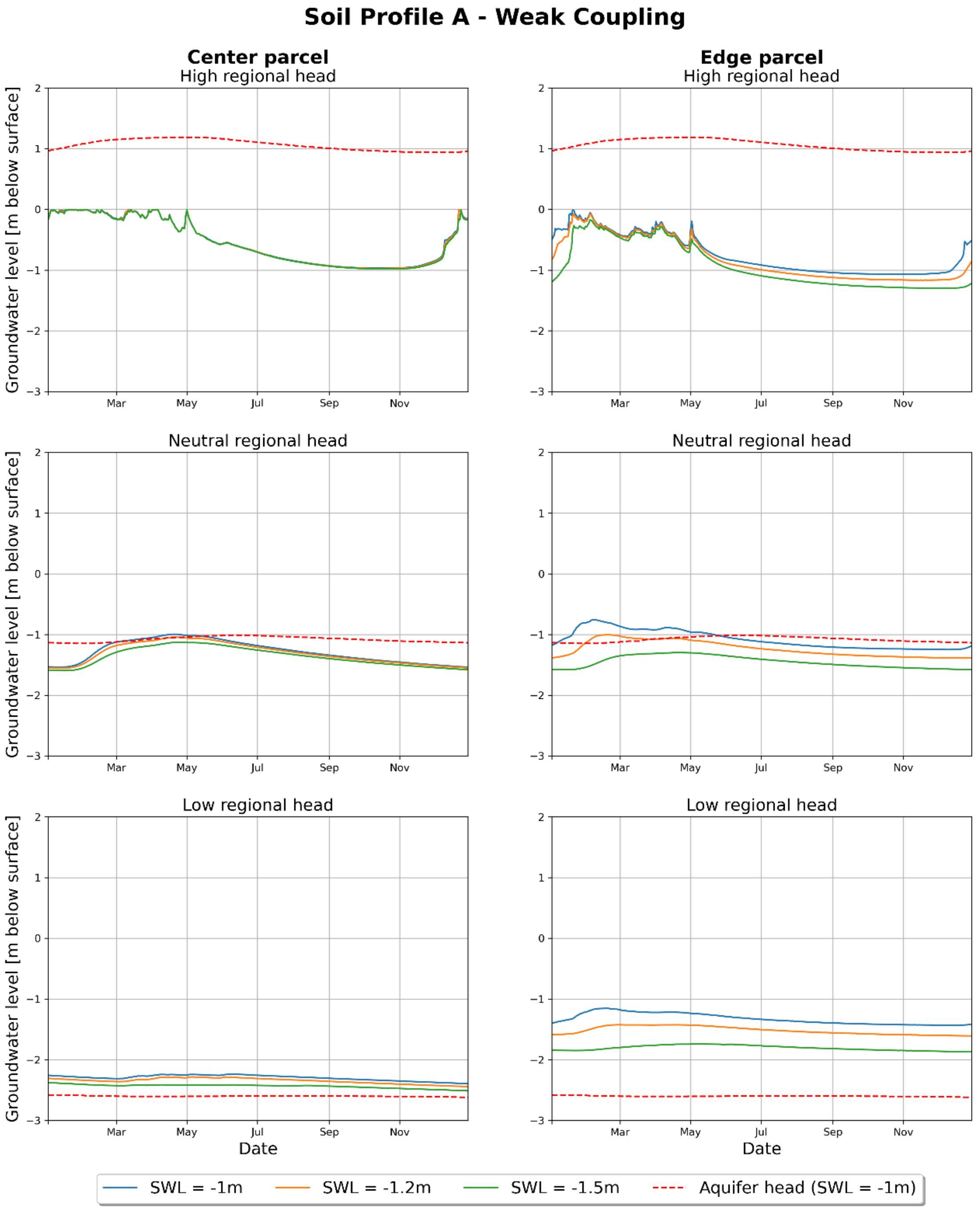

Soil Profile D - Strong Coupling
Center parcel
Edge parcel
High regional head
Neutral regional head
Low regional head
Groundwater level [m below surface]
2
1
0
−1
−2
−3
Mar
May
Jul
Sep
Nov
Date
SWL = -1m
SWL = -1.2m
SWL = -1.5m
Aquifer head (SWL = -1m)

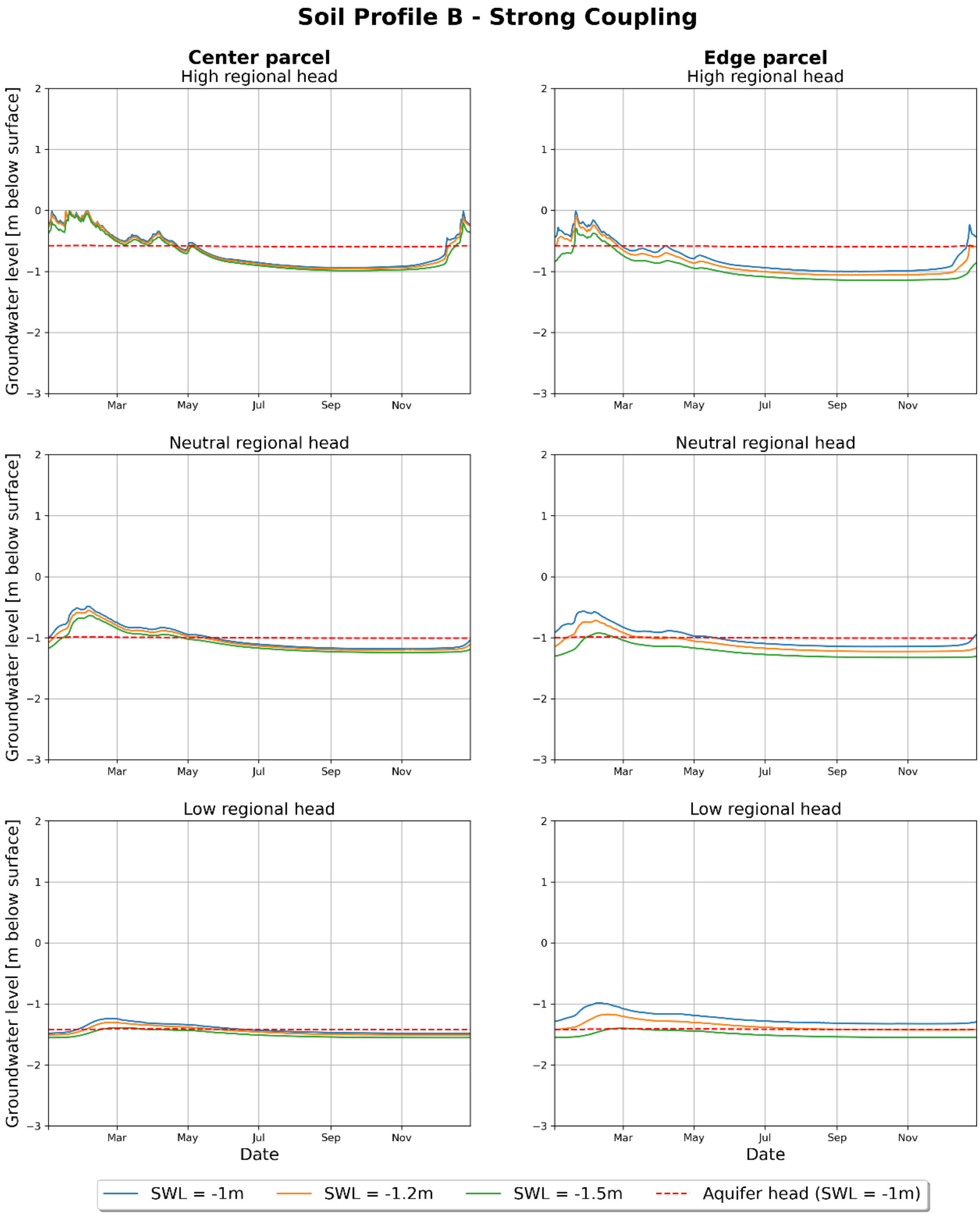

Soil Profile D - Weak Coupling
Center parcel
Edge parcel
High regional head
Neutral regional head
Low regional head
Groundwater level [m below surface]
2
1
0
−1
−2
−3
Mar
May
Jul
Sep
Nov
Date
SWL = -1m
SWL = -1.2m
SWL = -1.5m
Aquifer head (SWL = -1m)

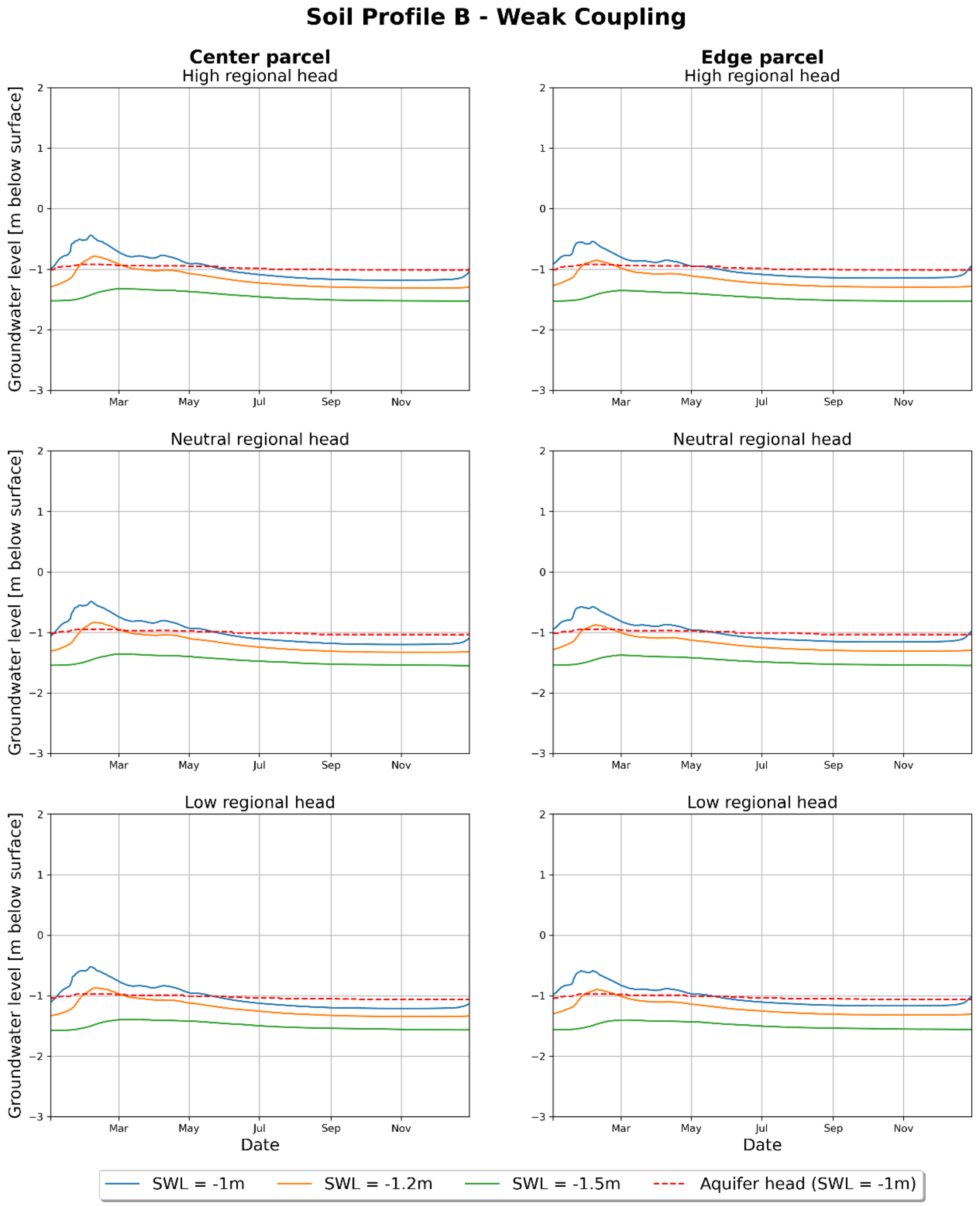
Appendix C7 Results (peat instead of clay) – GWT and hydraulic head time series

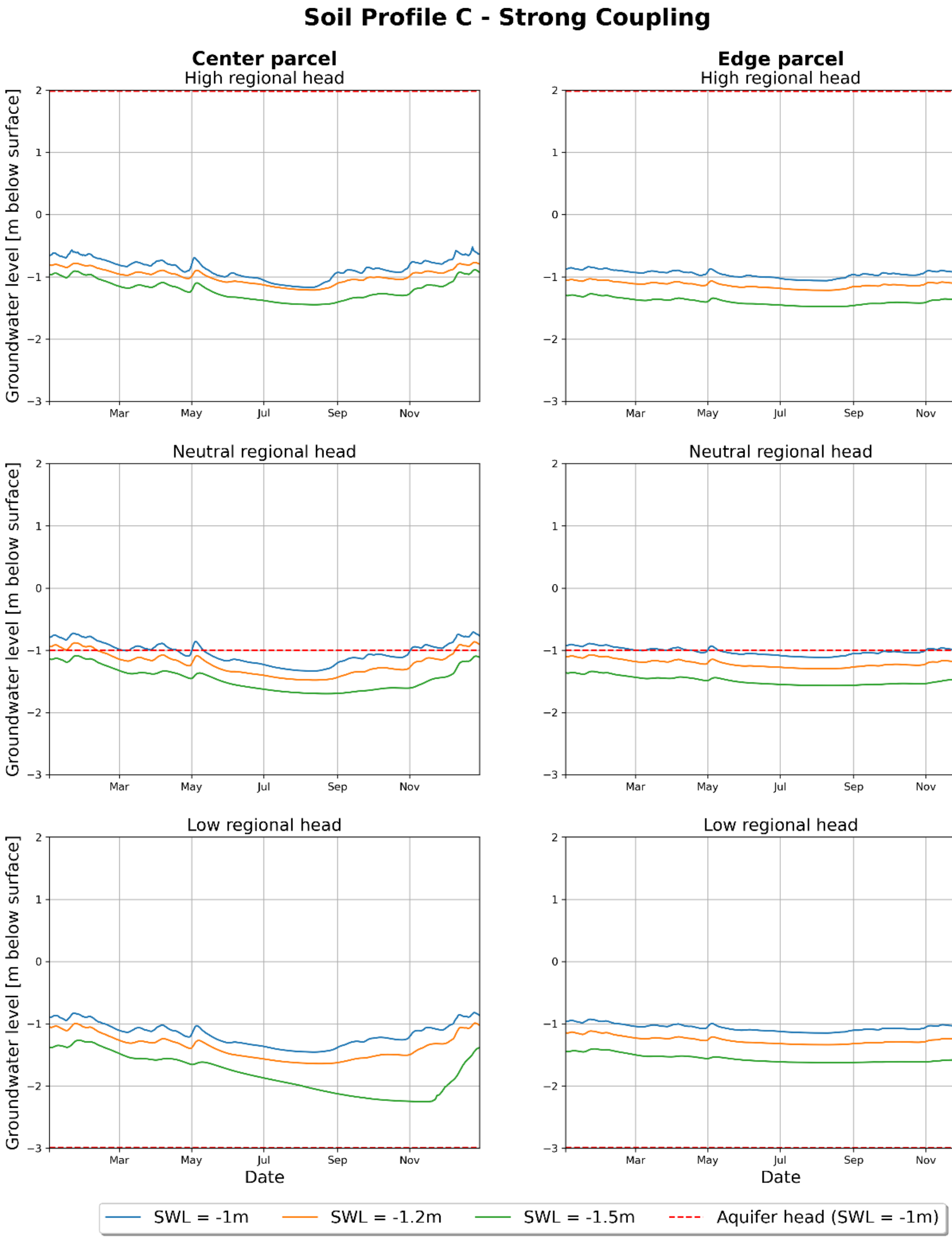
This appendix presents graphics of the GWT time series for the third year (2018). Left: centre of the parcel. Right: ‘edge’ of the parcel. The hydraulic head in the deep aquifer is depicted as well (only for the reference SWL). The difference between the aquifer head and GWT indicates if upward or downward seepage conditions prevail and the extent to which the aquifer head adjusts to the GWT changes (most apparent for weak coupling).




Soil Profile A - Weak Coupling
Center parcel
High regional head
Edge parcel
High regional head
Neutral regional head
Neutral regional head
Low regional head
Low regional head
Groundwater level [m below surface]
2
1
0
−1
−2
−3
Mar
May
Jul
Sep
Nov
Date
SWL = -1m
SWL = -1.2m
SWL = -1.5m
Aquifer head (SWL = -1m)


Soil Profile B - Strong Coupling
Center parcel
High regional head
Edge parcel
High regional head
Neutral regional head
Neutral regional head
Low regional head
Low regional head
Groundwater level [m below surface]
2
1
0
−1
−2
−3
Mar
May
Jul
Sep
Nov
Date
SWL = -1m
SWL = -1.2m
SWL = -1.5m
Aquifer head (SWL = -1m)


Soil Profile B - Weak Coupling
Center parcel
High regional head
Edge parcel
High regional head
Neutral regional head
Neutral regional head
Low regional head
Low regional head
Groundwater level [m below surface]
2
1
0
−1
−2
−3
Mar
May
Jul
Sep
Nov
Date
SWL = -1m
SWL = -1.2m
SWL = -1.5m
Aquifer head (SWL = -1m)



Soil Profile C - Strong Coupling

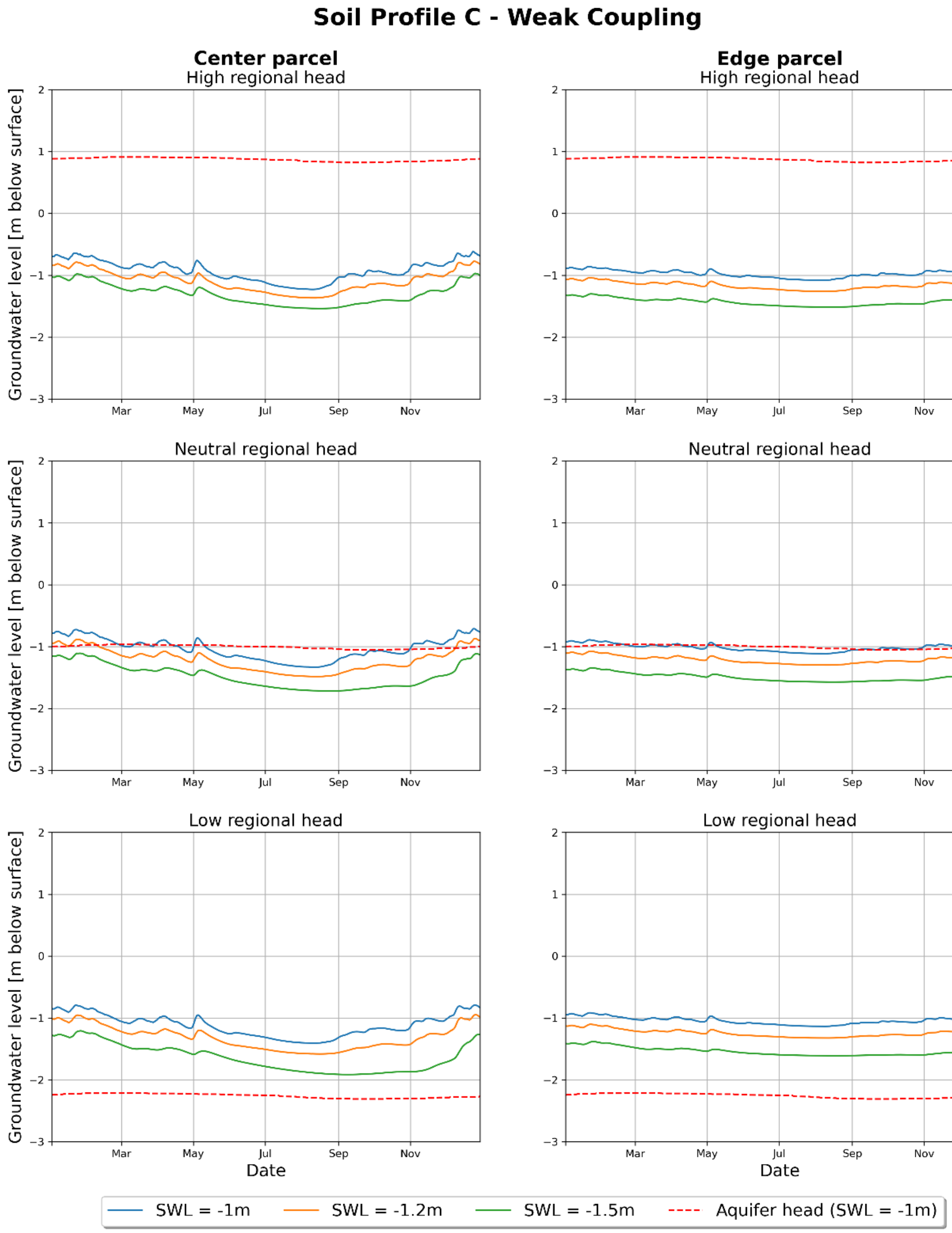
Center parcel

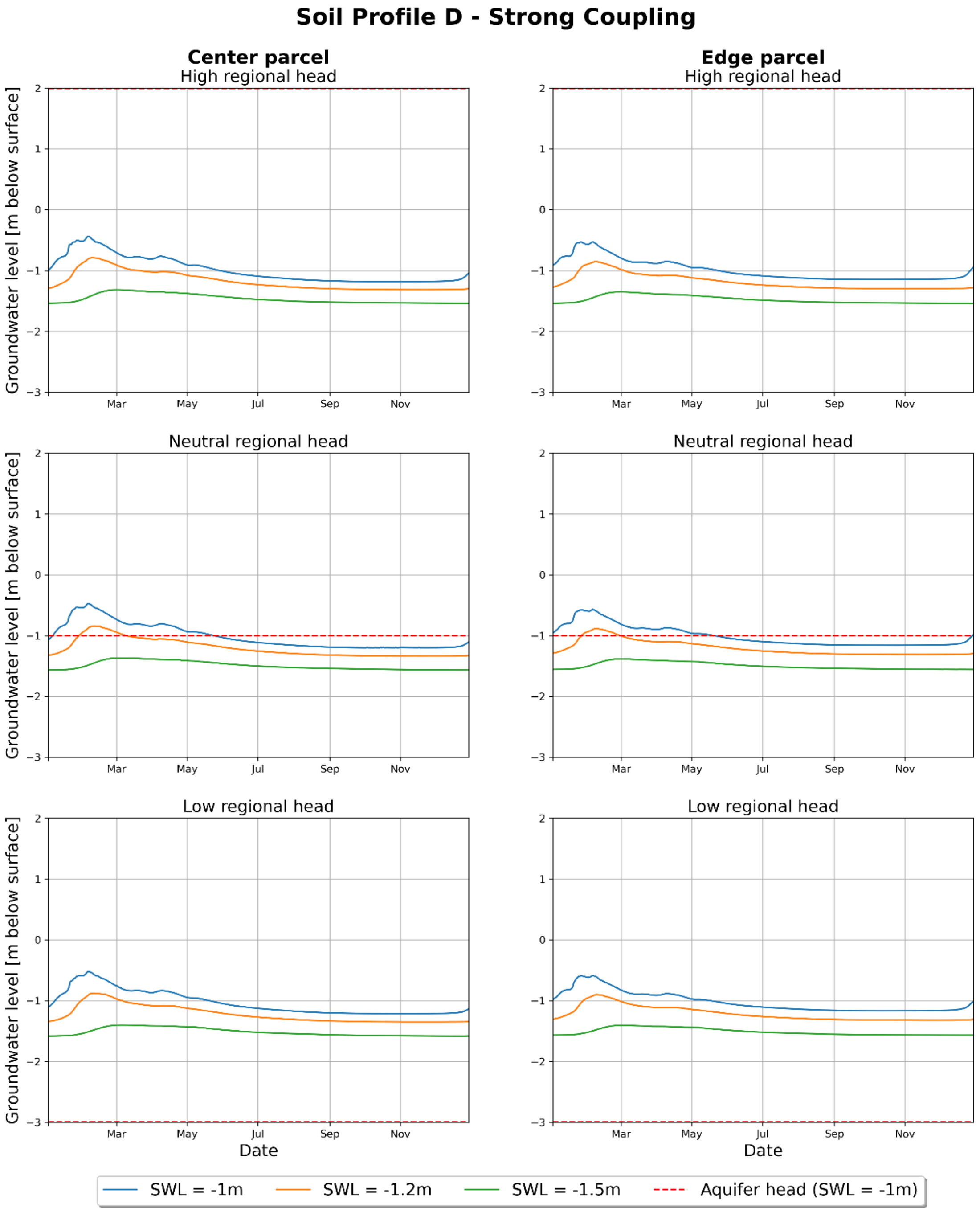
Edge parcel

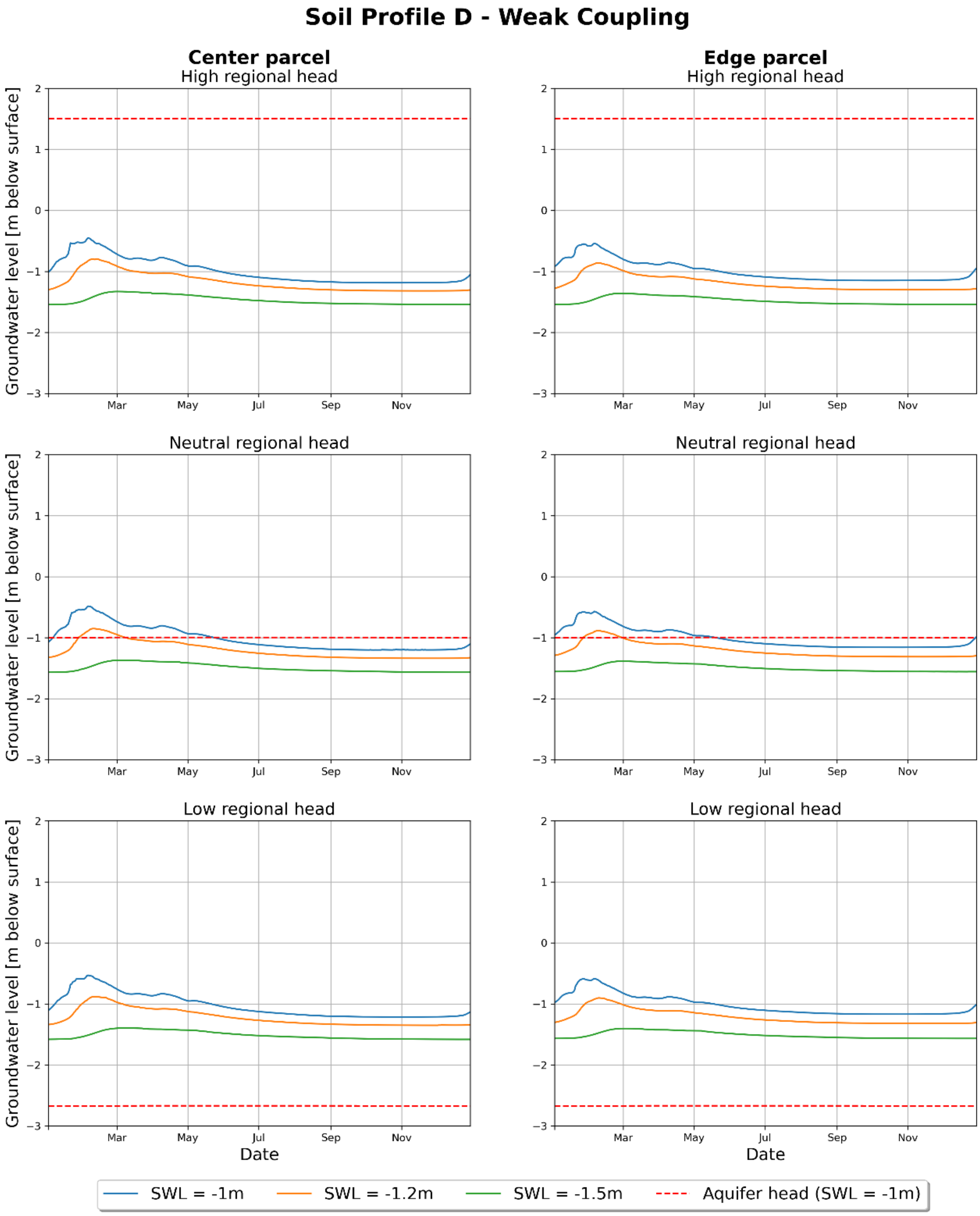
High regional head

Neutral regional head

Low regional head

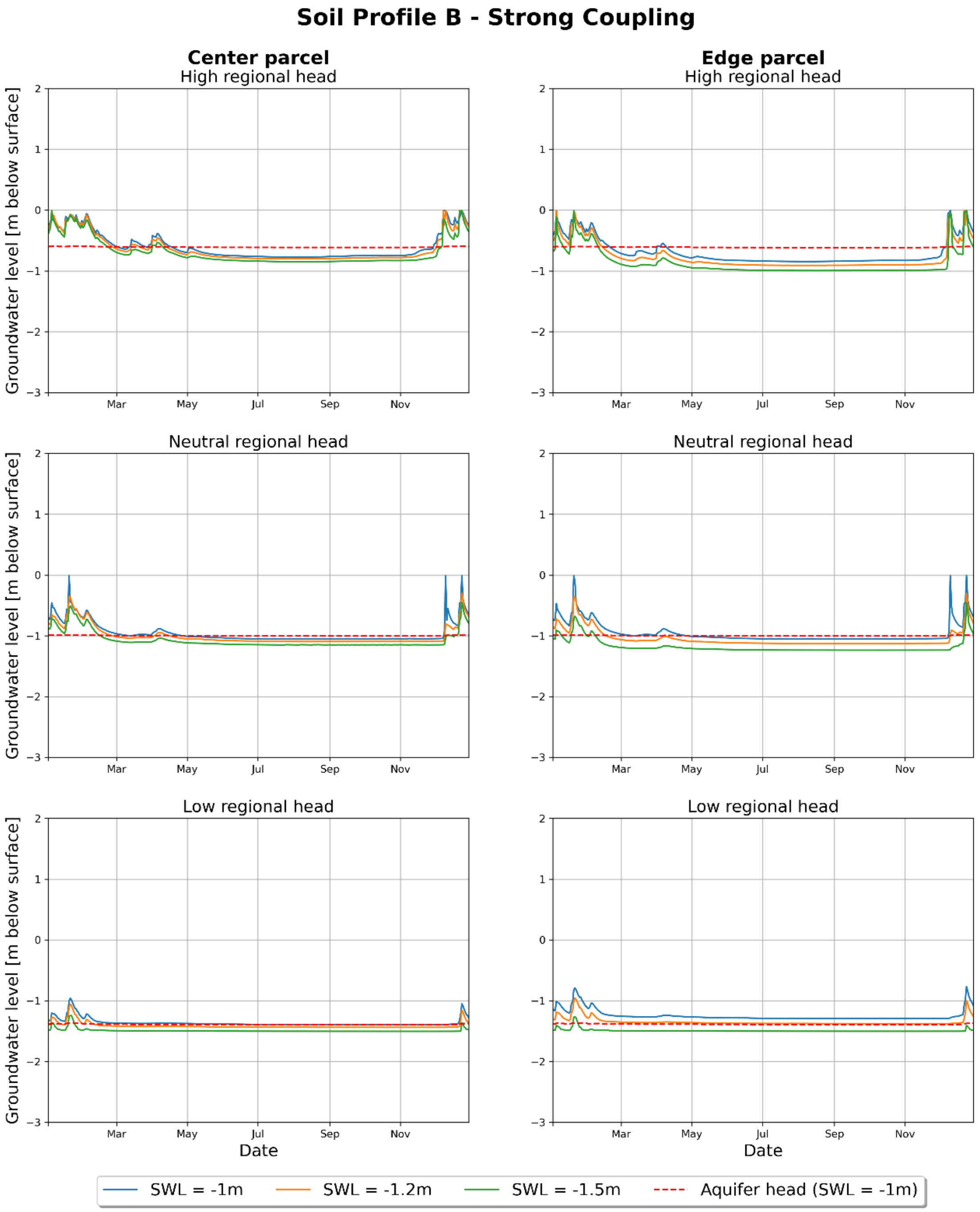

Soil Profile C - Weak Coupling
Center parcel
High regional head
Edge parcel
High regional head
Neutral regional head
Neutral regional head
Low regional head
Low regional head
Groundwater level [m below surface]
2
1
0
−1
−2
−3
Mar
May
Jul
Sep
Nov
Date
SWL = -1m
SWL = -1.2m
SWL = -1.5m
Aquifer head (SWL = -1m)

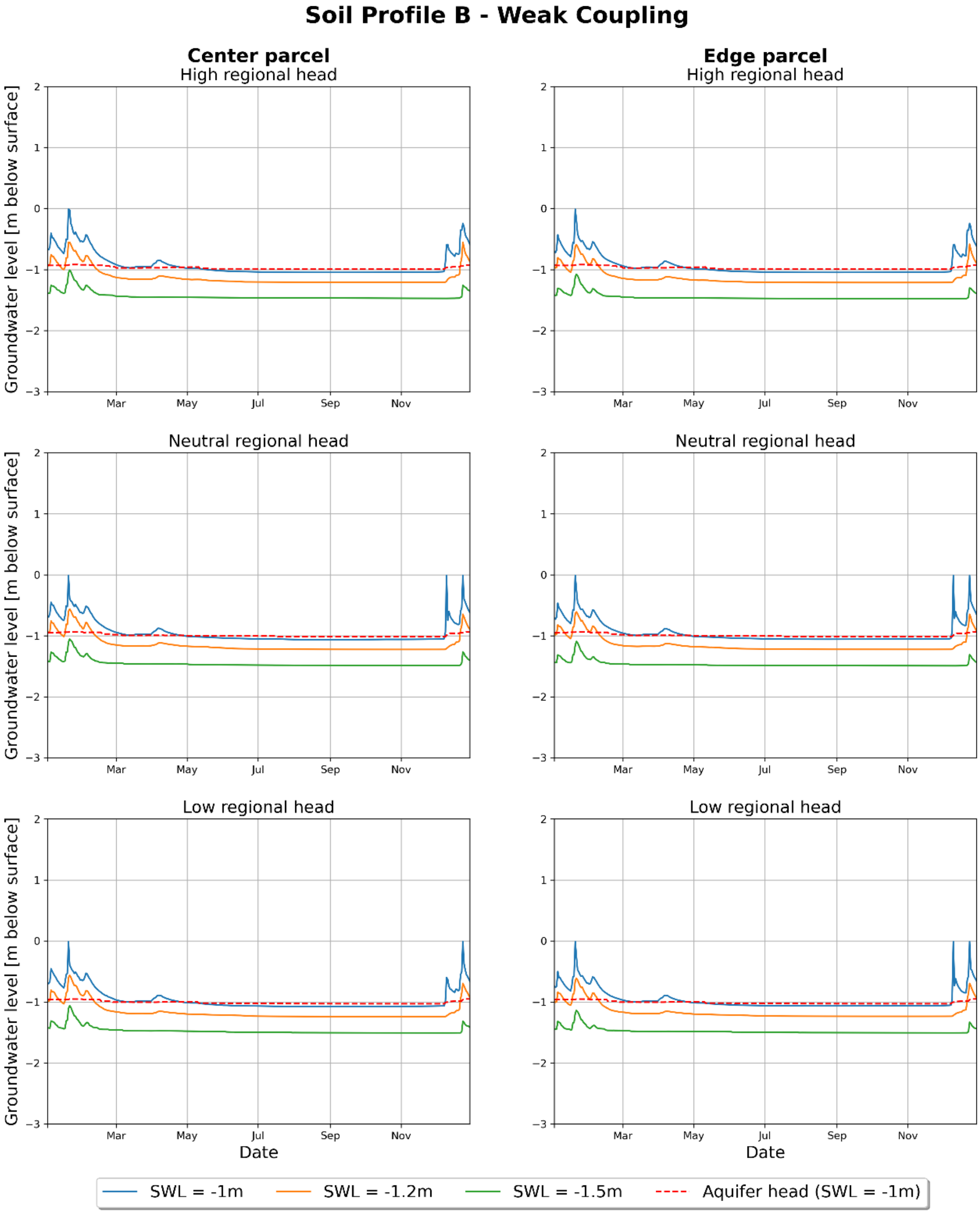

Soil Profile D - Strong Coupling
Center parcel
High regional head
Edge parcel
High regional head
Neutral regional head
Neutral regional head
Low regional head
Low regional head
Groundwater level [m below surface]
2
1
0
−1
−2
−3
Mar
May
Jul
Sep
Nov
Date
SWL = -1m
SWL = -1.2m
SWL = -1.5m
Aquifer head (SWL = -1m)

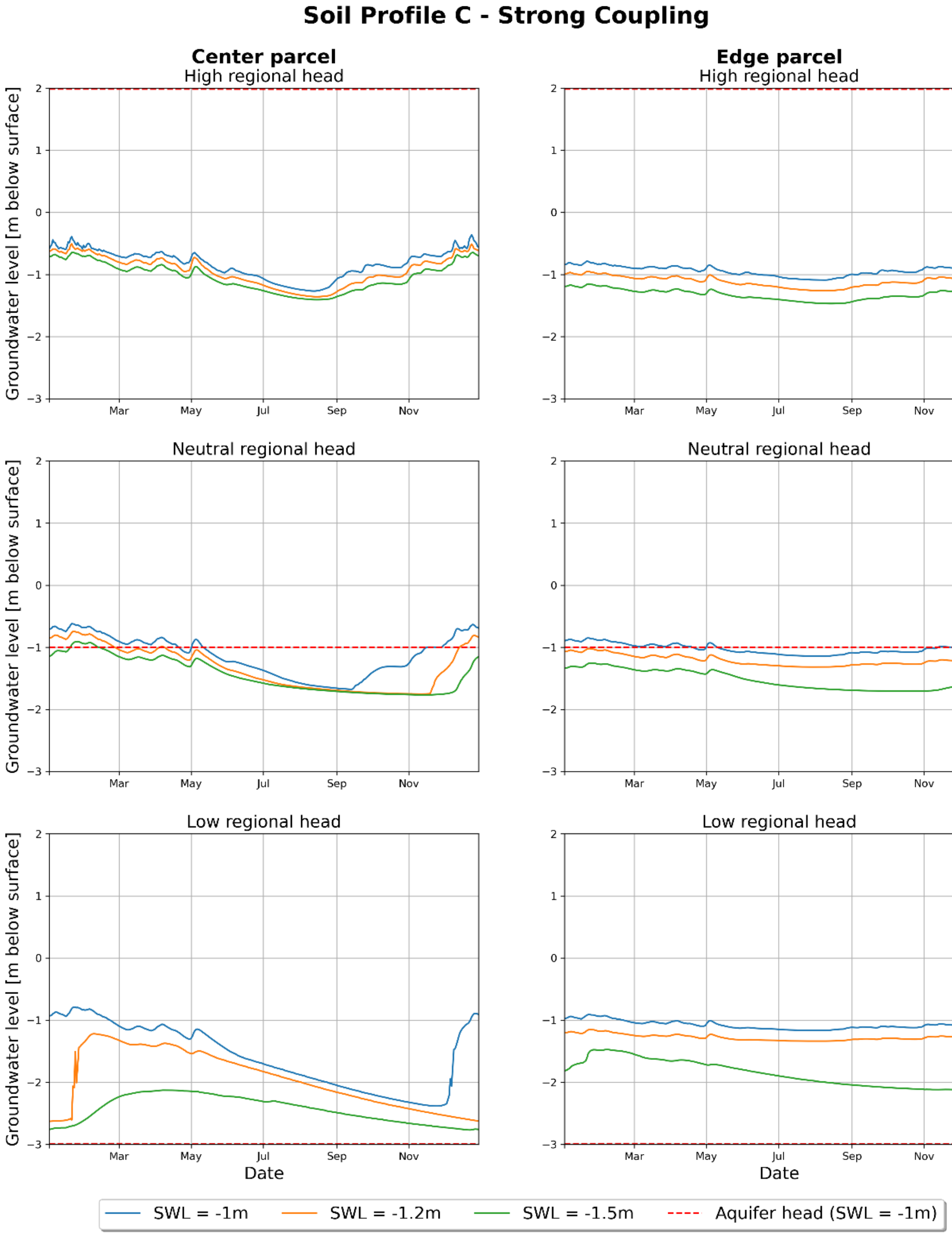

Soil Profile D - Weak Coupling
Center parcel
High regional head
Edge parcel
High regional head
Neutral regional head
Neutral regional head
Low regional head
Low regional head
Groundwater level [m below surface]
2
1
0
−1
−2
−3
Mar
May
Jul
Sep
Nov
Date
SWL = -1m
SWL = -1.2m
SWL = -1.5m
Aquifer head (SWL = -1m)

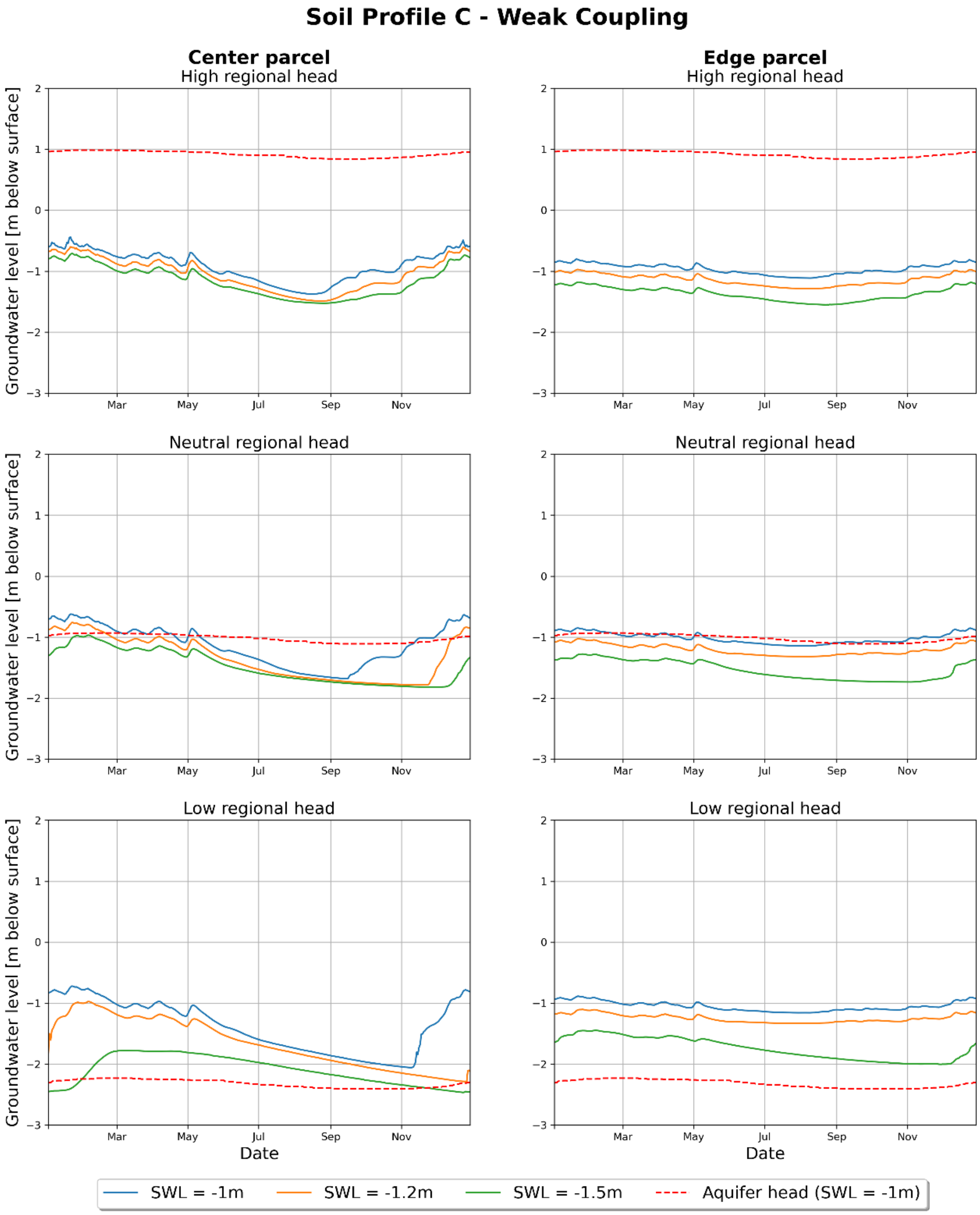
Appendix C8 Results (thinner top soil) – GWT and hydraulic head time series

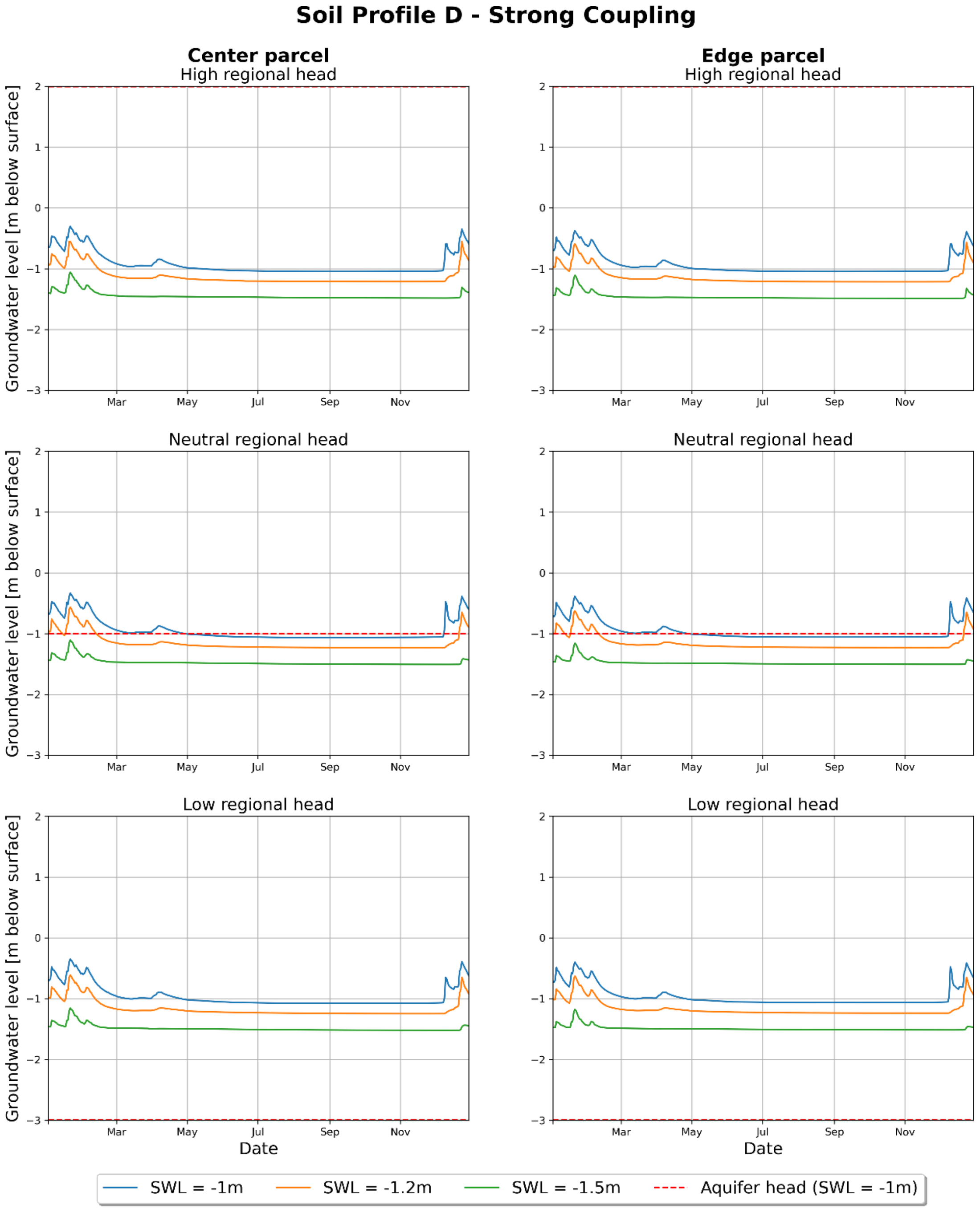
This appendix presents graphics of the GWT time series for the third year (2018). Left: centre of the parcel. Right: ‘edge’ of the parcel. The hydraulic head in the deep aquifer is depicted as well (only for the reference SWL). The difference between the aquifer head and GWT indicates if upward or downward seepage conditions prevail and the extent to which the aquifer head adjusts to the GWT changes (most apparent for weak coupling).

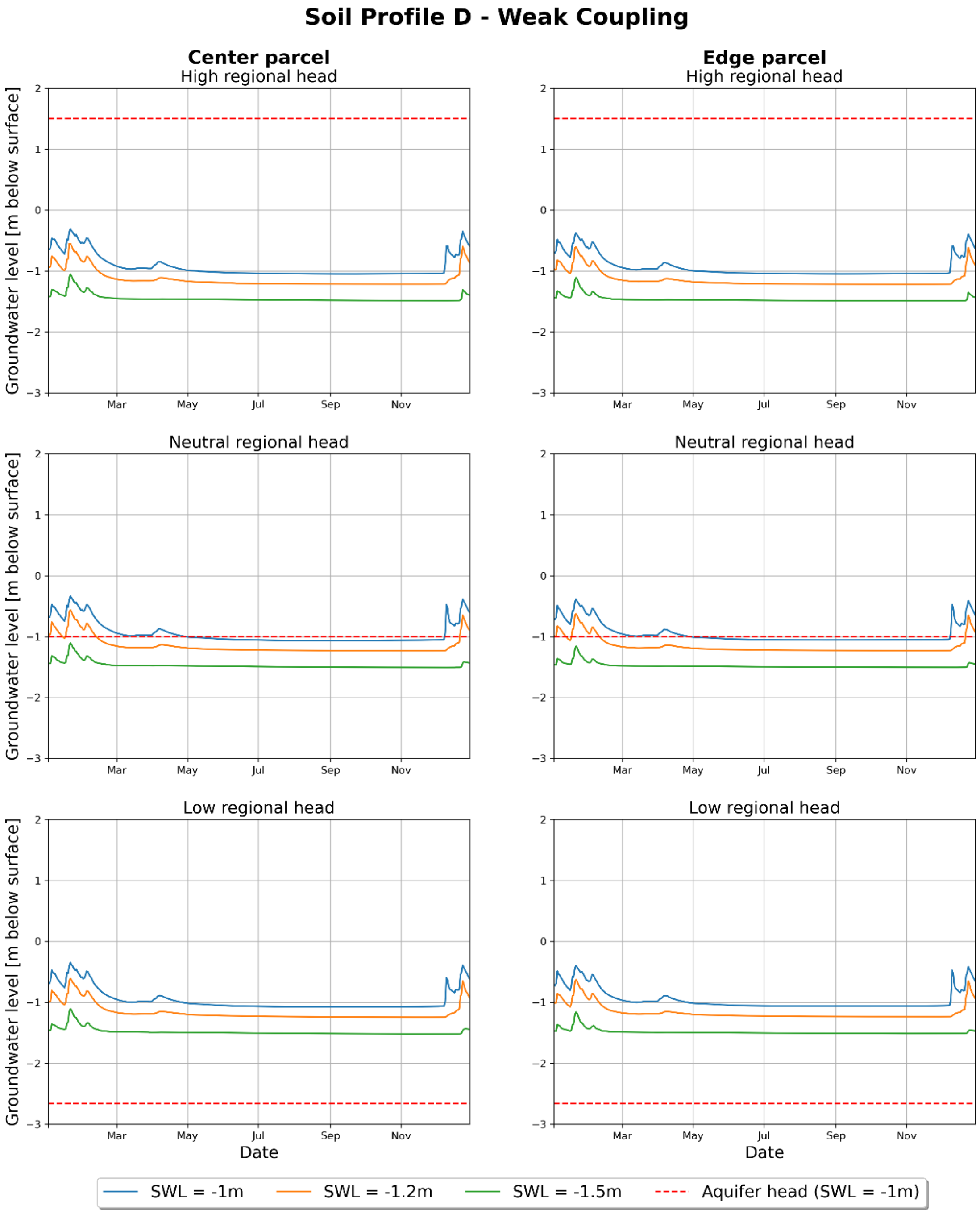



Soil Profile B - Weak Coupling
Center parcel
Edge parcel
High regional head
Neutral regional head
Low regional head
Groundwater level [m below surface]
2
1
0
−1
−2
−3
Mar
May
Jul
Sep
Nov
Date
SWL = -1m
SWL = -1.2m
SWL = -1.5m
Aquifer head (SWL = -1m)


Soil Profile C - Strong Coupling
Center parcel
High regional head
Edge parcel
High regional head
Neutral regional head
Neutral regional head
Low regional head
Low regional head
Groundwater level [m below surface]
2
1
0
−1
−2
−3
Mar
May
Jul
Sep
Nov
Date
SWL = -1m
SWL = -1.2m
SWL = -1.5m
Aquifer head (SWL = -1m)


Soil Profile C - Weak Coupling
Center parcel
High regional head
Edge parcel
High regional head
Neutral regional head
Neutral regional head
Low regional head
Low regional head
Groundwater level [m below surface]
2
1
0
−1
−2
−3
Mar
May
Jul
Sep
Nov
Date
SWL = -1m
SWL = -1.2m
SWL = -1.5m
Aquifer head (SWL = -1m)


Soil Profile D - Strong Coupling
Center parcel
Edge parcel
High regional head
Neutral regional head
Low regional head
Groundwater level [m below surface]
2
1
0
−1
−2
−3
Mar
May
Jul
Sep
Nov
Date
SWL = -1m
SWL = -1.2m
SWL = -1.5m
Aquifer head (SWL = -1m)


Soil Profile D - Weak Coupling
Center parcel
High regional head
Edge parcel
High regional head
Neutral regional head
Neutral regional head
Low regional head
Low regional head
Groundwater level [m below surface]
2
1
0
−1
−2
−3
Mar
May
Jul
Sep
Nov
Date
SWL = -1m
SWL = -1.2m
SWL = -1.5m
Aquifer head (SWL = -1m)

Appendix D Results – tabulated impact factors, compiled to compare base set and variants

D. 1 Soil Profile A

Soil profile A; strong coupling

		Mid parcel			'Edge parcel'		
regional head		high	neutral	low	high	neutral	low
∆SWL=-0.2m	Base case	0.00	0.00	0.00	0.28	0.52	0.78
	2016-2018 clim.	0.01	-0.01	-0.02	0.28	0.52	0.77
	Wide ditch	0.00	0.00	0.00	0.56	0.74	0.90
	Deepened ditch	0.00	0.01	-0.01	0.34	0.52	0.61
	Sand O1	-	-	-	-	-	-
	Clay O11	0.01	0.00	0.01	0.26	0.54	0.79
	Cl → Peat O16	0.00	0.04	0.11	0.42	0.65	0.92
	Thin cover layer	-	-	-	-	-	-
∆SWL=-0.5m	Base case	0.00	0.00	0.00	0.27	0.49	0.76
	2016-2018 clim.	0.00	0.00	0.00	0.27	0.49	0.76
	Wide ditch	0.00	0.00	0.01	0.55	0.71	0.90
	Deepened ditch	0.00	0.01	-0.01	0.36	0.51	0.61
	Sand O1	-	-	-	-	-	-
	Clay O11	0.00	0.00	0.01	0.26	0.52	0.77
	Cl → Peat O16	0.01	0.04	0.10	0.39	0.62	0.92
	Thin cover layer	-	-	-	-	-	-

Soil profile A; weak coupling							
		Mid parcel			‘Edge parcel’		
regional head		high	neutral	low	high	neutral	low
∆SWL=-0.2m	Base case	0.01	0.04	0.06	0.33	0.55	0.74
	2016-2018 clim.	0.02	0.03	0.08	0.34	0.54	0.73
	Wide ditch	0.01	0.03	0.16	0.60	0.75	0.89
	Deepened ditch	0.01	0.03	0.06	0.40	0.54	0.62
	Sand O1	-	-	-	-	-	-
	Clay O11	0.01	0.03	0.14	0.33	0.56	0.77
	Cl → Peat O16	0.03	0.08	0.25	0.49	0.70	0.87
	Thin cover layer	-	-	-	-	-	-
∆SWL=-0.5m	Base case	0.01	0.03	0.07	0.33	0.51	0.73
	2016-2018 clim.	0.00	0.03	0.00	0.33	0.51	0.71
	Wide ditch	0.01	0.04	0.11	0.60	0.73	0.88
	Deepened ditch	0.02	0.04	0.06	0.42	0.53	0.63
	Sand O1	-	-	-	-	-	-
	Clay O11	0.01	0.02	0.10	0.33	0.53	0.74
	Cl → Peat O16	0.02	0.11	0.23	0.46	0.66	0.88
	Thin cover layer	-	-	-	-	-	-

D.2 Soil profile B

Soil profile B; strong coupling							
		Mid parcel			‘Edge parcel’		
regional head		high	neutral	low	high	neutral	low
∆SWL=-0.2m	Base case	0.12	0.14	0.16	0.28	0.33	0.40
	2016-2018 clim.	0.12	0.14	0.16	0.28	0.33	0.40
	Wide ditch	0.15	0.20	0.23	0.58	0.63	0.69
	Deepened ditch	0.22	0.21	0.20	0.40	0.39	0.41
	Sand O1	-	-	-	-	-	-
	Clay O11	0.13	0.16	0.18	0.30	0.36	0.43
	Cl → Peat O16	0.08	0.11	0.14	0.30	0.40	0.51
	Thin cover layer	0.14	0.22	0.22	0.32	0.39	0.43
∆SWL=-0.5m	Base case	0.11	0.14	0.16	0.27	0.32	0.37
	2016-2018 clim.	0.11	0.14	0.16	0.27	0.32	0.37
	Wide ditch	0.15	0.20	0.23	0.57	0.62	0.66
	Deepened ditch	0.19	0.21	0.20	0.40	0.41	0.40
	Sand O1	-	-	-	-	-	-
	Clay O11	0.12	0.16	0.17	0.30	0.35	0.39
	Cl → Peat O16	0.09	0.12	0.14	0.29	0.36	0.45
	Thin cover layer	0.15	0.20	0.22	0.30	0.37	0.42

Soil profile B; weak coupling							
		Mid parcel			‘Edge parcel’		
regional head		high	neutral	low	high	neutral	low
∆SWL=-0.2m	Base case	0.80	0.78	0.77	0.83	0.81	0.80
	2016-2018 clim.	0.80	0.80	0.78	0.83	0.84	0.81
	Wide ditch	0.80	0.82	0.80	0.89	0.90	0.88
	Deepened ditch	0.88	0.83	0.81	0.88	0.85	0.83
	Sand O1	-	-	-	-	-	-
	Clay O11	0.86	0.88	0.86	0.89	0.90	0.89
	Cl → Peat O16	0.66	0.65	0.67	0.75	0.80	0.75
	Thin cover layer	0.81	0.81	0.84	0.83	0.83	0.85
∆SWL=-0.5m	Base case	0.81	0.81	0.81	0.83	0.83	0.84
	2016-2018 clim.	0.80	0.82	0.81	0.83	0.84	0.84
	Wide ditch	0.74	0.83	0.83	0.90	0.91	0.90
	Deepened ditch	0.86	0.85	0.85	0.88	0.87	0.87
	Sand O1	-	-	-	-	-	-
	Clay O11	0.89	0.88	0.88	0.91	0.90	0.90
	Cl → Peat O16	0.69	0.70	0.73	0.76	0.79	0.79
	Thin cover layer	0.85	0.85	0.87	0.87	0.87	0.88

D.3 Soil profile C

Soil profile C; strong coupling							
		Mid parcel			'Edge parcel'		
regional head		high	neutral	low	high	neutral	low
∆SWL=-0.2m	Base case	0.65	0.73	0.94	0.88	0.91	0.95
	2016-2018 clim.	0.63	0.73	0.94	0.88	0.91	0.95
	Wide ditch	0.66	0.74	0.94	0.90	0.92	0.95
	Deepened ditch	0.57	0.51	0.50	0.85	0.84	0.86
	Sand O1	0.38	0.54	0.75	0.75	0.83	0.89
	Clay O11	0.64	0.74	0.93	0.88	0.91	0.92
	Cl → Peat O16	0.21	0.73	0.93	0.78	0.91	0.95
	Thin cover layer	0.46	0.39	1.23	0.86	0.87	0.87
∆SWL=-0.5m	Base case	0.55	0.73	1.84	0.83	0.90	0.95
	2016-2018 clim.	0.55	0.73	1.85	0.83	0.90	0.95
	Wide ditch	0.57	0.74	1.66	0.86	0.92	0.96
	Deepened ditch	0.57	0.57	0.56	0.84	0.86	0.86
	Sand O1	0.39	0.60	0.94	0.75	0.85	0.95
	Clay O11	0.55	0.74	1.75	0.84	0.91	0.95
	Cl → Peat O16	0.55	0.73	1.59	0.83	0.90	0.95
	Thin cover layer	0.28	0.18	0.77	0.76	1.12	1.91

Soil profile C; weak coupling							
		Mid parcel			‘Edge parcel’		
regional head		high	neutral	low	high	neutral	low
∆SWL=-0.2m	Base case	0.67	0.76	0.88	0.89	0.92	0.94
	2016-2018 clim.	0.61	0.76	0.88	0.87	0.92	0.94
	Wide ditch	0.70	0.76	0.85	0.91	0.92	0.94
	Deepened ditch	0.53	0.49	0.51	0.85	0.83	0.86
	Sand O1	0.44	0.57	0.68	0.78	0.84	0.88
	Clay O11	0.65	0.76	0.90	0.89	0.91	0.94
	Cl → Peat O16	0.69	0.75	0.87	0.89	0.92	0.94
	Thin cover layer	0.57	0.53	1.20	0.87	0.88	0.87
∆SWL=-0.5m	Base case	0.61	0.77	1.04	0.87	0.91	0.95
	2016-2018 clim.	0.61	0.75	1.03	0.87	0.91	0.95
	Wide ditch	0.63	0.78	1.01	0.89	0.93	0.95
	Deepened ditch	0.56	0.58	0.58	0.84	0.86	0.87
	Sand O1	0.46	0.63	0.83	0.78	0.86	0.93
	Clay O11	0.61	0.78	1.07	0.87	0.92	0.95
	Cl → Peat O16	0.62	0.77	1.02	0.87	0.92	0.95
	Thin cover layer	0.30	0.28	0.82	0.87	1.18	1.69

D.4 Soil profile D

Soil profile D; strong coupling							
		Mid parcel			'Edge parcel'		
regional head		high	neutral	low	high	neutral	low
∆SWL=-0.2m	Base case	0.80	0.81	0.81	0.82	0.82	0.84
	2016-2018 clim.	0.79	0.81	0.81	0.82	0.82	0.84
	Wide ditch	0.81	0.80	0.82	0.90	0.90	0.89
	Deepened ditch	0.87	0.86	0.87	0.88	0.86	0.88
	Sand O1	-	-	-	-	-	-
	Clay O11	0.88	0.90	0.90	0.90	0.91	0.91
	Cl → Peat O16	0.66	0.69	0.68	0.76	0.76	0.77
	Thin cover layer	0.83	0.85	0.86	0.84	0.86	0.87
∆SWL=-0.5m	Base case	0.84	0.84	0.84	0.85	0.86	0.87
	2016-2018 clim.	0.84	0.84	0.84	0.85	0.86	0.87
	Wide ditch	0.84	0.85	0.85	0.91	0.92	0.91
	Deepened ditch	0.87	0.88	0.89	0.89	0.89	0.90
	Sand O1	-	-	-	-	-	-
	Clay O11	0.91	0.92	0.92	0.93	0.93	0.94
	Cl → Peat O16	0.71	0.73	0.73	0.78	0.79	0.80
	Thin cover layer	0.87	0.88	0.89	0.88	0.89	0.90

Soil profile D; weak coupling							
		Mid parcel			'Edge parcel'		
regional head		high	neutral	low	high	neutral	low
∆SWL=-0.2m	Base case	0.80	0.81	0.80	0.82	0.82	0.82
	2016-2018 clim.	0.80	0.82	0.81	0.83	0.83	0.83
	Wide ditch	0.81	0.81	0.82	0.90	0.90	0.89
	Deepened ditch	0.85	0.86	0.86	0.88	0.86	0.87
	Sand O1	-	-	-	-	-	-
	Clay O11	0.89	0.90	0.90	0.91	0.92	0.91
	Cl → Peat O16	0.67	0.68	0.68	0.76	0.76	0.76
	Thin cover layer	0.83	0.85	0.86	0.85	0.86	0.87
∆SWL=-0.5m	Base case	0.84	0.84	0.84	0.86	0.86	0.86
	2016-2018 clim.	0.84	0.84	0.84	0.86	0.86	0.87
	Wide ditch	0.85	0.85	0.85	0.91	0.92	0.91
	Deepened ditch	0.87	0.88	0.89	0.89	0.89	0.90
	Sand O1	-	-	-	-	-	-
	Clay O11	0.92	0.92	0.92	0.93	0.93	0.93
	Cl → Peat O16	0.71	0.73	0.73	0.79	0.80	0.79
	Thin cover layer	0.88	0.88	0.89	0.89	0.90	0.90

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