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PEER REVIEW OF SAMPHIRE WATER USE MODELLING

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1 Executive Summary

This report is a scientific and technical rThis report is a scientific and technical review of a draft report by Fortescue Metals Group (FMG) entitled:

Modelling Analysis of the Impact of Mine Dewatering on Soil Water Availability to the Samphire Vegetation on the Fringe of Fortescue Marsh

hereafter referred to as the Report (FMG, 2013). Proposed changes to dewatering activities at the Christmas Creek Life of Mine project may lower the water table below samphire vegetation communities of conservation value. The Report is a modelling study investigating potential changes to the soil hydrology and water consumption by samphire plants across the affected area. It concludes that planned dewatering will have minimal impact upon samphire communities fringing the Fortescue Marsh.

The scope of this review is to comment on the scientific basis of the modelling, the soundness of the adopted assumptions and the resulting conclusions drawn in that report. The review examined the modelling of soil hydrology and plant physiology (plant water use) and the conservativeness of adopted assumptions.

This review makes the following findings:

1. The use of compensated root water uptake will lead to erroneous conclusions when applied over large spatial domains.

   This occurs when the area occupied by the roots in the model is much larger than the typical lateral extent of a single plant’s rooting system, as was the case here. While there appears to be evidence for compensated root water uptake from the available data the problem lies with the inability of the numerical code to simulate the hydrology of individual plants. As a result, predicted transpiration rates could be over estimated and the likelihood of permanent wilting reduced in comparison to the case where compensation occurs only at the individual plant level.

2. By neglecting salinity in the soil the simulations may be wrongly describing where the plants are obtaining water from, with flow on effects to the resulting water balance that could either over- or under-estimate the potential for permanent wilting to occur.

   The sensitivity of samphire plants to both fresh water and highly saline conditions was not simulated in the report. The sensitivity to salinity was shown in experimental work to vary by species, from highly tolerant for those located in the centre of the Marsh to slightly less tolerant for those that occupy the fringe zone. Spatial differences in tolerance to water stress varied opposite to that of salinity. These differences should be considered in modelling efforts. Observations of water uptake suggest that salinity may be involved in compensated water uptake to some extent and to impact the temporal variation in vertical water consumption by plants. The current presentation of the existing experimental data is not sufficient to support the choice of stress function parameterisation.

3. There was an inconsistent use of conservative and non-conservative assumptions in derivation of the model and its parameterisation.

   Many of the assumptions were conservative in nature, however there were several assumptions that were not conservative. Among them included the:
   - estimation of soil evaporation rates and the dependence upon the fractional area occupied by plant canopies;
   - impact of salinity upon plant function and stress;
   - higher than observed root densities, both high and deep within the soil profile and the limited assessment of rooting distributions in the sensitivity analysis;
   - few soil properties assessed, particularly the lack of coarser soils tested in simulations.
   - Incorrect calibration of the transpiration coefficient, Kcb, and failure to account properly for water stress/hydraulic properties or salinity which limits transpiration rates during the dry season.

This review makes the following recommendations:
1. Consider reappraising the experimental data and presenting the data more completely within the Report, particularly the water potential / vegetation stress data, including the methodology adopted.
2. Increase the value of Kcb so peak transpiration rates are closer to observed and to calibrate the stress function, water retention curve(s), and or salinity stress to better capture transpiration rates during the dry season.
3. Include salinity in the simulation and modelling to better account for the impact of total water potential (osmotic + matric) upon the occurrence of permanent wilting and patterns of water use.
4. Reconsider the need for 2-D simulations and instead, or as well, consider the use of 1-D simulations in order to allow better simulation of compensated root water uptake.
5. If 2-D simulations are considered necessary then an alternative modelling approach should be considered, whereby individual plants and their root systems can be simulated.
6. Adjust the lower boundary condition in order to allow better assessment of the possible changes in the water table due to large rain events and prolonged drying.
7. Change the assumed impact of canopies upon potential soil evaporation rates as the current approach likely significantly underestimates its contribution to water fluxes.
8. Improve the uncertainty analysis by considering a wider variety of soil hydraulic properties in simulations.
9. Consider simulations and experiments to assess the role of episodic flood events on the recruitment and establishment of samphire species and their spatial distribution.

2 Introduction

Fortescue Metals Group (FMG) conducted a modelling study for the purpose of assessing the potential impacts to samphire plant species in and adjacent to the Fortescue Marsh from proposed dewatering activities at the Christmas Creek Life of Mine operation (FMG, 2013). The samphires, highly salt tolerant halophytes, are considered to be of conservation value.

The modelling study consisted of the implementation of a two-dimensional (2-D) numerical model representing the saturated and unsaturated water flow processes in the vertical and the horizontal directions, occurring along an approximately 1 km transect across the inner-Marsh through the outer-Marsh fringe zone. Across this area there is a transition from a dense samphire group to a sparse samphire region. This change in vegetation composition was specifically modelled.

The aims of the modelling exercise were to assess the potential for the plants to maintain their water consumption post dewatering and to avoid permanent wilting, a state where the soil becomes too dry and the plants potentially die. Experimental work by UWA has shown that the samphires rarely recover if they experience significant wilting (Equinox, 2013).

FMG commissioned A/Prof. Gavan McGrath, of the University of Western Australia to produce this review of the modelling undertaken. McGrath is an Environmental Engineer by training and completed a PhD from UWA in the area of soil physics in 2007. He currently conducts hydrologic, eco-hydrologic and soil physics related research and teaches unsaturated water flow, eco-hydrology and contaminant fate and transport at UWA.

2.1 Aims and Objectives

The aim of this report is to comment on the validity of the science underpinning the Report, the modelling, the assumptions used and thus the suitability of the conclusions drawn.

The objectives of the peer review are to:

- Review the assumptions underpinning the HYDRUS model and discuss its limitations
- Evaluate the suitability of the model setup
- Audit copies of the implemented model along with the data used to run it
- Comment on the implementation of the numerical model to the problem at hand
- Comment on the results of the numerical model and the associated conclusions

Table 1: HYDRUS Input files.

Input File	Description
ATMOSPH.IN	Specifies differing surface boundary fluxes over the Dense Samphire and Sparse Samphire zones, transpiration rates of plant type 1.
BOUNDARY.IN	Specifies the types of boundary conditions simulated and the nodes of the finite element mesh that constituted boundary nodes
Options.in	Details the parameters of the Feddes water uptake stress function for the plant type 2 as well as the temporal variation in the transpiration rates of this plant type.
MESHTRIA.TXT	Details the coordinates of each finite element node and the element boundaries.
DOMAIN.DAT	which specifes each node, its initial matric potential, the root densities of type 1 and type 2 plants at each node, and the boundary code (if any), associated with the node.
SELECTOR.IN	Specifies many of the simulation control options, the soil hydraulic parameters and the Feddes parameters for plant type 1.

2.2 Scope of Review

This peer review is limited to the Report only. However, in addition this review took into consideration studies on the eco-physiology of the samphire communities previously conducted by UWA, and any reports documenting the soil-hydrologic characteristics of the Marsh soils, as deemed appropriate by FMG. This included a summary report Fortescue Marsh: Synthesis of eco-hydrological knowledge, 2013 by Equinox Environmental Pty Ltd for Fortescue Metals Group and personal communication with Professor Erik Veneklaas, The University of Western Australia. Finally the review checked a copy of the HYDRUS files used to run the modelling for the report and audit them for consistency with documented methods, parameterisation and results. The report, associated studies and the modelling files were supplied by FMG.

3 Review Methodology

This review examined several features of the Report with a particular emphasis on the modelling, the parameterisation of the model, the assumptions used and the conservativeness of the approach. This included reading published articles by UWA scientists examining the physiology of several samphire species from the Marsh, as well as an overview report by Equinox summarising current understanding of the eco-hydrology of the Marsh system (Equinox, 2013).

An overview of the assumptions and limitations of the physics underpinning the simulation of water flow is briefly provided, which is based upon the reviewers expertise and lecturing experience at UWA.

The construction of the model is examined and includes interrogation of the boundary conditions, initial conditions, parameterisation and the processes simulated. The boundary conditions, for example, control the amount of water that enters and leaves the model domain, but also the way in which that water then moves within it. The interrogation of model construction was assessed via the input data files, which are summarised in Table 1.

For the purpose of assessing the hydrology a simplified version of the simulation model was implemented in HYDRUS 2-D/3-D version 1.xxx (Šimůnek et al., 2006), an earlier version of the model as used in the Report.

In addition to viewing the files provided, computer scripts were used to extract the data and plot, boundary conditions, initial conditions, material distributions as well as results of simulations generated specifically for this Review. The data files provided for assessment are detailed in Table 2.

4 Results and Discussion

The results of the review and discussion of implications is separated into several sections representing key aspects of the modelling exercise. First a brief overview of the basic assumptions behind the HYDRUS model is discussed along with some definitions of terminology. This is followed by a description and appropriateness of the boundary conditions applied in Sections x to x. A brief comment on the spatial and temporal discretization of the model is made in Sections x and x. Next an in depth analysis of the plant physiological modelling is made in Section 5.9, with particular emphasis given to the application of compensated root water uptake.

4.1 Water Flow Physics

The modelling was conducted using the software HYDRUS 2D/3D marketed by PC Progress, Czech Republic. HYDRUS has a long history of use in industry and in scientific applications (Šimůnek and Hopmans, 2009; Vanderborght et al., 2010; Sutanto et al., 2012; Deb et al., 2013) as well as significant development, improvement, and correction of errors since the first public release of the code in 1998 (Šimůnek et al., 1998; Simůnek et al., 2006) that had been developed from several earlier numerical codes (Šimůnek and Suarez, 1993).

Water flow in the unsaturated zone is often simulated using Richards Equation, the basis of HYDRUS (Richards, 1931). Richards Equation is the unsaturated analogue of Darcy’s Law for saturated water flow, whereby water flows from high to low energy potentials. In unsaturated soils the energy of a parcel of water is comprised of several components, including the surface tension forces of cohesion and adhesion, otherwise known as matric potential, osmotic forces related to differences is solute concentration and gravitational potential due to elevation differences i.e. :

$$\psi_{total} = \psi_{matric} + \psi_{osmotic} + \psi_{elevation}$$

Table 2: Summary of simulation input files provided for this review.

File Name	Project/Scenario Description
PreMiningDry	Pre-mining groundwater level under 3-year Dry weather spells assuming fully compensated root water uptake
PreMiningWet	Pre-mining groundwater level under 3-year Wet weather spells assuming fully compensated root water uptake
DDN1Dry	1-m drawdown from pre-mining groundwater level under 3-year Dry weather spells assuming fully compensated root water uptake
DDN1Wet	1-m drawdown from pre-mining groundwater level under 3-year Wet weather spells assuming fully compensated root water uptake
DDN2Dry	2-m drawdown from pre-mining groundwater level under 3-year Dry weather spells assuming fully compensated root water uptake
DDN2Wet	2-m drawdown from pre-mining groundwater level under 3-year Wet weather spells assuming fully compensated root water uptake
DDN2Dry_nonCompen	2-m drawdown from pre-mining groundwater level under 3-year Dry weather spells assuming non-compensated root water uptake
DDN2Wet_nonCompen	2-m drawdown from pre-mining groundwater level under 3-year Wet weather spells assuming non-compensated root water uptake
DDN3Dry	3-m drawdown from pre-mining groundwater level under 3-year Dry weather spells assuming fully compensated root water uptake
DDN3Dry_nonCompen	3-m drawdown from pre-mining groundwater level under 3-year Dry weather spells assuming non-compensated root water uptake
DDN2Dry7MPa	2-m drawdown from pre-mining groundwater level under 3-year Dry weather spells assuming fully compensated root water uptake (base case); Matric potential at permanent wilting point is increased to -7 MPa for sensitivity analysis
DDN2Dry1_5Static	2-m drawdown from pre-mining groundwater level under 3-year Dry weather spells assuming fully compensated root water uptake (base case); Static canopy interception of rainwater is increased by 50% for sensitivity analysis
DDN2Dry1_5Kcb	2-m drawdown from pre-mining groundwater level under 3-year Dry weather spells assuming fully compensated root water uptake (base case); Basal plant coefficient is increased by 50% for sensitivity analysis
DDN2DryBareSparse	2-m drawdown from pre-mining groundwater level under 3-year Dry weather spells assuming fully compensated root water uptake (base case); Canopy coverage of the sparse vegetation segment is reduced to 0 for sensitivity analysis
KcbCalib	Calibration of basal plant coefficient against measured sap flow
PrfValid	Validation simulation of soil water content against sampled profiles at the UWA pits (CC1, CC3 and CC4)

In order for a plant to take up water from the soil the potential energy of water within the plan has to be lower than that of the water in the soil. For horizontal water flow into a root the elevation potential can be ignored. Therefore, in circumstances when the salt concentration is not toxic to a plant the sum of matric and osmotic potentials need to be overcome in order for a plant to transpire and fix carbon for growth.

Some succulent plants can manipulate their internal osmotic status to maintain transpiration in salty soils, although there are complex physiological constraints regulating these processes (English and Colmer, 2013). During severe droughts the forces acting on water across the soil-plant-atmosphere continuum can cause the hydraulic apparatus, the xylem, within plants to be damaged. When severe stress occurs the xylem can be damaged beyond repair, leading to permanent wilting. The permanent wilting point is not a fixed number but varies considerably from species to species and also within species. For agricultural crops in humid climates a value of the permanent wilting point often assumed is -1500 kPa, while some eucalypts are known to survive soil matric potentials
less than -5000 kPa.

The explicit assumptions of Richards Equation are many but of relevance here they include:

- the porous medium does not deform and the pore space does not change with time;
- the hydraulic properties of the medium vary smoothly in space such that at the macroscopic scale (the scale of modelling) the physics of the micro-scale (or pore scale) processes remain the same, albeit with effective parameters that average sufficiently;
- the density of the fluid does not change;
- there is a consistent and quantifiable relationship between capillary forces in soil, the amount of water the soil holds and the conductivity of the medium to water flow;

These assumptions are violated in many instances. For example, Richards Equation is known to be incompatible with many observations of preferential water flow in soil, that is water which infiltrates at the soil surface and rapidly moves to depth through cracks, along animal burrows and root channels, bypassing the majority of the soil profile (Flury et al., 1994). Structured soils are particularly susceptible to preferential flow, although even well sorted sandy soils have the potential to display preferential flow processes that can’t be simulated by HYDRUS (Fürst et al., 2009). Some dual permeability options for simulating preferential flow are implemented in HYDRUS, however, they still have significant limitations and are difficult to parameterise (Köhne et al., 2002).

The hydraulic conductivity of an unsaturated soil depends sensitively upon the degree of saturation. When fully saturated it is composed of the fluidity and the permeability. Permeability is often assumed to be an intrinsic property of the pore space however soils with fluctuating salt contents can cause the mobilisation of clay minerals leading to spatial and temporal fluctuations in permeability. Rearrangement of the pore space due to crusting can significantly impact the unsaturated hydraulic conductivity for example. In addition soil salinity can induce changes in the forces holding water in soil as well as changes in the density of water thus altering not only the hydraulic conductivity of the liquid in soil but also the gross flow patterns via density-dependent flow (e.g. Bradford and Tokzaban, 2009). The degree to which the soils shrink and swell will depend upon their mineralogy and in particular the types of clay minerals present. The fluidity, on the other hand, is the related to the viscosity and density of the fluid, both of which are affected by changes in the salt content. The extent to which salinity plays a significant role in unsaturated water flow in the soils at the study site is currently unknown.

The use of Richards Equation for the simulation of hydrological processes in unsaturated sols is the default standard when there is little evidence to suggest its limitations may be violated. No dye tracer studies appear to have been conducted to suggest that preferential flow, for example, is a significant process in the study soils. Reports of the soil texture suggest that Richards Equation could be reasonably valid in the rather homogeneous surface sandy loams. However, angular-blocky aggregates in the deeper clay suggest a susceptibility to preferential water flow (Flury et al., 1994; FMG, 2013; Equinox, 2013). The rapid filling of macropores, rather than the entire soil matrix, following large rain events may be responsible for rapid rises in groundwater levels observed (Equinox, 2013). Macropores, if present, could also impact the spatial distribution of roots and the spatio-temporal variability of readily available soil moisture. The extent to which the soils at the site violate the assumed physics appears to require further investigation.

4.2 Applied Boundary Conditions

The dynamics of water flow in HYDRUS are governed by the boundary conditions. In this instance the boundary conditions include the top, bottom and sides of the modelled spatial domain. The choice of boundary conditions is important as they can have a significant impact upon the dynamics of water flow and thus the final conclusions drawn from the modelling effort.

An interrogation of the types of boundary conditions, as extracted from the input files, is shown in Figure 1. Three of the four boundary conditions applied are shown. The fourth, a no flow boundary, is uncoded in the HYDRUS input file, but should be interpreted as occurring along the side boundaries on the left and right. Over the region specified as Dense Samphire an atmospheric boundary condition is applied (cf. Figure 4 of the Report). Over the area specified as Sparse Samphire a variable flux boundary condition is applied. At the lower boundary a constant head boundary is applied.

4.2.1 Surface Boundary Conditions

A limitation of HYDRUS is that only one atmospheric boundary condition can be applied. As an objective of the modelling was to account for spatial differences in interception and evaporation across two vegetated zones, an alternative boundary condition over the Sparse Samphire zone was applied as a variable flux boundary condition.

An atmospheric boundary is a special “System Dependent” boundary condition (Šimůnek et al., 2006). The potential fluxes of water entering/leaving the soil, *E*, are dependent upon the unsaturated hydraulic conductivity of the soil near the surface in the following way:

$$\left|\left(K\frac{\partial h}{\partial x}+K\right)\right| \leq E$$

where, h is the matric potential at the soil surface, x is a direction, and K is the unsaturated hydraulic conductivity. The matric potential at the surface is limited to values such that: $h_A < h < h_S$ i.e. the pressure head is limited to a certain height of ponding of water above the soil surface and to a minimum value related to equilibrium of soil with the relative humidity of the atmosphere. When the above equality cannot be met then the boundary switches to a constant head boundary, the value taking on either h_A and h_S as appropriate.

For a time variable flux boundary the following is satisfied:

$$\left|\left(K\frac{\partial h}{\partial x}+K\right)\right| = E$$

In the latest version of HYDRUS the constraint $h_A < h < h_S$ can still be applied to a time variable flux boundary to make it appear as a second atmospheric condition. An inspection of the input file Boundary.in indicates that the variable Atm/WL was set to *true,* indicating that the time-variable flux boundary condition was treated similarly as the atmospheric boundary conditions, i.e., with limiting pressure head values h_A and h_S.

The values h_A and h_S are therefore critical in modulating water fluxes during dry and wet periods respectively. In the Report a h_S value of 0 was adopted which effectively means that rainfall in excess of the soils capacity to infiltrate it is removed as “surface runoff” and is not redistributed elsewhere in the modelled domain. For conservative modelling to assess drought potential then this is appears to be a reasonable assumption. However, the degree to which this is conservative is significantly affected by the temporal resolution of modelling. When averaging rainfall at daily time scales, as was the case in the report, short duration, high intensity rain events, which would produce runoff, could be reduced to daily events with much lower intensity that would satisfy conditions to completely infiltrate. Therefore the amount of runoff simulated depends sensitively upon the temporal resolution adopted (McGrath et al., 2008).

The choice of h_A is also significant for controlling bare-soil evaporation rates when the soil is drying. The value of h_A should be calculated from the relative humidity i.e.

$$h_A = \frac{R\,T}{M\,g}\ln H_r$$

where M is the molecular weight of water, g is the gravitational acceleration, R is the universal gas constant, T the temperature and H_r the relative humidity. In practice it is recommended that h_A is less than the permanent wilting point and values in the literature often use the recommended value of -1000 m H2O (Vanderborght et al., 2010; Sutanto et al., 2012). In the report a value of -1001 m H2O was used; 1 m less than the adopted permanent wilting point.

Based upon measured temperatures and relative humidities from the Pilbara midday values of h_A could be expected to exceed -3000 m H2O (Bureau of Meteorology, 2014). Values of this order would increase soil evaporation and dry surface soils more than simulated in the Report. The cost, however, would be a greatly increased potential for numerical instability (and/or increase simulation time) at the commencement of intense rain events. This is a trade-off that can only be weighed by the significance of soil evaporation to the water balance.

Table 3: Excerpt from ATMOSPH.IN input file and calculations on that data.
tAtm denotes the time corresponding to the atmospheric/time variable boundary flux, Prec is the precipitation rate, rSoil is the potential soil evaporation rate, rRoot is the potential transpiration rate from soil, rt is the time variable boundary flux, rT/rSoil is the ratio of rT to rSoil, and –(rt-10 rSoil) is the effective precipitation rate simulated for the Sparse region.

tAtm (day)	Prec (m/day)	rSoil (m/day)	rRoot (m/day)	rt (m/day)	rt/rSoil (-)	-(rt-10 rSoil) (m/day)
1	0	0.000310	0.000393	0.003100	10	0
2	0	0.000415	0.000526	0.004150	10	0
3	0	0.000410	0.000520	0.004100	10	0
4	0	0.000375	0.000475	0.003750	10	0
5	5.40E-05	0.000430	0.000545	0.003764	8.8	5.40E-04
6	0	0.000435	0.000551	0.004350	10	0
7	0	0.000385	0.000488	0.003850	10	0
8	0	0.000415	0.000526	0.004150	10	0
9	0	0.000390	0.000494	0.003900	10	0
10	0	0.000395	0.000501	0.003950	10	0
11	0	0.000425	0.000539	0.004250	10	0
12	0	0.000405	0.000513	0.004050	10	0
13	1.04E-04	0.000450	0.000570	0.003457	7.7	1.04E-03
14	0	0.000375	0.000475	0.003750	10	0
15	0	0.000355	0.000450	0.003550	10	0
16	0	0.000420	0.000532	0.004200	10	0
17	0	0.000435	0.000551	0.004350	10	0
18	0	0.000340	0.000431	0.003400	10	0
19	6.40E-05	0.000405	0.000513	0.003407	8.4	6.40E-04
20	2.80E-05	0.000360	0.000456	0.003317	9.2	2.80E-04
21	3.70E-05	0.000345	0.000437	0.003076	8.9	3.70E-04
22	7.622E-03	0.000370	0.000469	-0.007702	-20.8	1.14E-02

The potential flux at the surface, *E*, an input to the model simulations, is also a critical factor. In the Report several assumptions are made regarding rainfall interception and the partitioning of potential evaporation at the soil surface. Principal among these is the assumption that there is no soil evaporation from below the canopy (see the first term on the right hand side of Equation 1 in the Report). A critique of the estimation of *E* is given in the following paragraphs.

One component of *E* that was missing was surface runoff. The marsh appears to receive considerable inflows via overland flow during extreme rainfall events, often tropical cyclones, yet this modelling did not take these inflows into account (Equinox, 2013). The effect of this for simulations of “wet years” is to effectively underestimate the duration and extent of flooding and soil wetness. For dry year simulations this should have little impact.

Several ATMOSPH.IN files, which provide the fluxes that control the atmospheric and time variable flux boundary conditions, were examined to assess the impact of the assumed partitioning of soil evaporation and infiltration. The net flux at the surface for an atmospheric boundary is given by the difference between the columns, *Prec* and *rSoil* in the ATMOSPH.IN file, while the time variable boundary condition is specified by the column *rt*. Plots of rSoil and precipitation for simulations DDN1Dry and DDN1Wet are shown in Figures 2 and 3.

It is apparent from these input files that the potential soil evaporation rate in the Dense Samphire Zone is 1/10th that in the Sparse Samphire Zone (Table 1). In addition, the effective precipitation rate (i.e. precipitation – interception) is between 1 and 10 times greater in the Sparse Zone than the Dense Zone. During relatively intense rainfall the ratio declines to values around 1, as would be expected. Rainfall rates are generally 10 times lower in the dense region when the daily rain rate is less than 5 mm/day (see Table 3 and Figure 4 and Figure 5).

The reasoning for assuming that the presence of a denser canopy will reduce potential soil evaporation rates by 10 times does not appear to be supported by the empirical evidence. For example, the measurement of bare soil evaporation rates in open areas and under a canopy near Perth has shown that soil evaporation rates in the open were at most twice those under a canopy (Gwenzi et al., 2012). Similarly, Scott et al., (2006) found bare soil evaporation to constitute between 30% and 70% of the total evapotranspiration flux in a shrubby desert environment, depending upon the time since rainfall. Still others have found only minor differences in soil evaporation rates). Given that the canopies of dessert plants rarely completely shade the soil, that wind can penetrate beneath low lying canopies and temperatures of soils below such canopies still gets quite high the assumption of zero evaporation from under canopies is not particularly conservative in this context.

The estimation of interception loss is based upon the experiments of Dunkerly (2008) and the model proposed by Wang (2012), however neither reference was present in the bibliography. Nevertheless the interception loss, Pc, is calculated via:

$$P_c = (1 + ET_0) f_c$$

where ET_0 is the crop reference evapotranspiration and f_c is the faction of area covered by canopy. The equation assumes 1 mm/rain day is evaporated from the canopy at a minimum as well as however much is the potential evaporation that day. As an assumption its effect is to predict lower infiltration than may actually occurs and is therefore considered conservative.

4.2.2 Side boundaries

The Report implemented no-flow conditions at the side boundaries. For the left boundary (representing the inner marsh) this no-flow condition is considered to be a reasonable choice representing conditions closer to the centre of the marsh. If conditions were mirrored on the other side of the marsh then close to the centre any horizontal water flow would be expected to be small in comparison to vertical water fluxes.

The rightmost boundary was chosen to be a no flow boundary as well. This boundary represents the side closest to the dewatered zone. The choice of a no-flow boundary on the right has implications for how saturated zone water fluxes are simulated. Such a choice would mean that any significant lateral fluxes would only be generated by spatial differences in infiltration and evaporation. According with the prescribed top-boundary conditions (see below) the model would simulate greater infiltration and lower transpiration on the right compared to the left of the modelled domain, thus potentially causing greater recharge of groundwater on the right than the left (i.e. centre of marsh). However, the lower boundary condition would ensure there is no flow of saturated water towards the Marsh centre.

Other options for the right hand boundary could have included: a constant head to represent the impact of drawdown and allow an assessment of lateral water fluxes; time variable head to assess time-frames for the propagation of saturated zone levels during the dewatering process until steady conditions are achieved; or constant flux to represent the effect of dewatering at the right hand boundary.
All these options however have problems in the current context. A constant-head boundary on part of the right hand boundary could potentially represent well the conditions much further from the Marsh, closer to the location of dewatering, however this would come at the expense of much increased computation time. Flux boundaries are problematic, particularly at vertical boundaries with variably saturated conditions. A no-flow boundary therefore appears to be the best compromise.

4.2.3 Lower boundary condition

The lower boundary adopted is a constant head boundary across the whole length of the modelled domain. This has pros and cons. The primary advantage of a constant head lower boundary is that it is simple and can maintain saturation of at least part of the domain. However, there are several disadvantages in the use of a constant head lower boundary and more significantly there is a lack of justification for specifying the spatial distribution of the water table elevation.

One limitation related to the definition of the lower boundary as having a constant head is that the water table does not change position, even after a significant drought, or significant recharge. As a result the thickness of the unsaturated zone does not change in any simulations. The superficial aquifer in the Marsh is known to experience water table fluctuations of the order of 2 – 3 m annually in response to significant rain events (Equinox, 2013). It is currently unknown how the water table responds to prolonged drought. Nevertheless, for the objectives of the Report, an alternative lower boundary that could better simulate the dynamic nature of the water table, would be to apply a tile-drain lower boundary condition. For such a condition the flux of water leaving the lower boundary is proportional to the pressure head there but this flux is constrained by the hydraulic conductivity of the drain, thereby allowing the water table to rise and fall. In addition, the use of such a boundary would allow the use of piezeometric data as part of the calibration process.

A further consequence of a constant head lower boundary is its potential impact upon computation speed. Large groundwater recharge events have the potential to cause significant increases in the flux across the lower boundary in order to maintain a constant head. This has the potential to increase the number of iterations and to lower the time step during these periods. In addition, all the nodes below the water table are redundant and could have been omitted to speed computation time.

Perhaps more significantly there is important information missing with regard the current nature of the groundwater levels in the area. While Figures 2 and 3 in the Report show the projected drawdown in groundwater levels over the area, neither the supplied Equinox report nor this Report show the current water table elevations. Therefore, it is not possible to tell from the information presented how the drawdown relates to a change in the elevation of the water table over the study area.

The Equinox report indicates that groundwater is a subdued expression of the topography. Therefore some justification is required for the use of a water table at a constant elevation of 398 m. Based upon Figure 3 of the Report, the predicted drawdown varies from 1 - 3 m per kilometre over the study site. The topography rises by approximately 3 m per kilometre suggesting that at least at the upper end of drawdown there will be a hydraulic gradient lowering the water table upslope. Therefore, instead of the lower parts of the root zone being within 2 m of the water table near the right hand boundary as they are currently simulated, they could instead be 5 m above the water table. The impact of this upon the plants upslope would depend upon the nature of the soils and groundwater salinity.

4.3 Spatial and temporal discretization

The spatial distribution of nodes of the finite element mesh can be seen in Figure 6. The nodes have an appropriately high resolution near the soil surface and within the root zone. Such a high resolution would be required for these simulations as there are likely to be rapid transitions from very dry to very wet soils. The soil properties are distributed as described in the Report with a shallow layer of loam, overlying a clay loam. The soil hydraulic parameters in the input file was consistent with that reported.

In addition the spatial distribution of root densities was consistent with those in the Report (see Figure 7). However, the modelled root distributions were greater than observed below 1.5 m depth and between 0.5 m and 1.0 m depth. The potential impact of this is to simulate greater uptake of water from near the water table an from shallow rain events. The impact of this is not fully understood as compensated root water uptake may partly account for this in any case.

4.4 Model Calibration and Validation

There appeared to be a reasonable calibration of modelled evapotranspiration (ET) and observed ET. However, modelled ET was systematically lower than observed ET during the wet period. This may result from a number of factors, including: that a reduction in salinity stress at this time favoured higher evaporation rates; that soil water was held in macropores at this time; or that the hydraulic properties of the soils differed to those modelled.

The model calibration process involved adjusting the value of K_{cb}, the value that adjusts the simulated transpiration to observed levels. Part of the calibration process involved taking multiple realisations of the initial conditions from repeated simulations of the available 3 years of weather data collected at the site. There should have been a critique of how representative the prevailing conditions were prior to the beginning of the model simulation period. This could easily have been done by reviewing the regional climate from longer term Bureau of Meteorology data as well as reports on the climate in the region by CSIRO. From personal experience the previous 10 years had experienced relatively dry conditions as compared to the rainfall data collected during the UWA monitoring period. This suggests much drier initial conditions than simulated. In addition there is no reporting of the time of year at which initial conditions were taken from and whether there was consideration of the seasonality in doing so.

Nevertheless, given the uncertainty, the use of an ensemble of initial conditions is a useful approach. In order to provide some ability to interpret the impact of the variability in initial conditions it would be useful to provide error bars as indicators of the uncertainty and variability simulated. In addition some comment regarding the over prediction of transpiration during the dry period and significant under prediction of peak transpiration rates during the wet periods should have been made. As there was no calibration of soil parameters these hydraulic properties could play a significant role in regulating transpiration rates. The over prediction during the dry could be caused by number of factors, from: an overestimation of the unsaturated hydraulic conductivity of the soil; underestimation of how high the permanent wilting point is; or underestimating the impact of changing salinity as soils dry. The calibration and/or uncertainty analysis did not consider these factors.

The underestimation of transpiration during the wet must point to a higher K_{cb} than calibrated, as this is the number limiting the potential value and not the value of transpiration when limited by water and/or salinity stress. Therefore as higher K_{cb} should be adopted and consideration of other effects limiting transpiration during drier times should be explored.
Model validation was conducted by comparing gravimetrically measured water contents to volumetric predictions of soil water content with depth at two time intervals. The adopted single bulk density to estimate volumetric water content adds significant uncertainty to the measured values. In addition it takes no account of spatial variability in bulk density. On this basis statements that the data and model agree reasonably well or that model over estimates the data should be properly qualified with regard the uncertainty introduced by not measuring simultaneously bulk density and volumetric water contents in the field.

4.5 Hydro-Climatological and Dewatering Scenarios

A stochastic rainfall simulator is used to generate realisations of rainfall for 3 year dry and 3 year wet simulation scenarios. Rainfall in the Pilbara is correlated with the El Nino Southern Oscillation, and has been shown to fluctuate at decadal time scales (McGrath et al., 2013). It is not clear whether this simulator takes account of serially correlated annual rainfall series that would enhance the probability of dry years following dry years and wet years following wet years.

An inspection of the initial conditions, as specified in the input files DOMAIN.DAT, was conducted. The initial conditions for simulations appears to be different with “Wet” simulations tending to have wet initial conditions while “Dry” simulations appearing to have comparatively dry initial conditions (see Figures 8 to 18). The text in the Report is unclear as to how the initial conditions were derived for the scenario simulations. Given that the initial conditions are different it is unclear how the various scenarios are compared to one another. In addition the sensitivity of results to the initial conditions does not appear to have been assessed.

Interestingly the initial conditions for matric potential in soil show in many instances large areas of the soil below wilting point. In fact several simulations showed initial matric potentials at or below permanent wilting throughout the profile (e.g. Figure 10, and Figure 17). In addition there were few locations with potentials much lower than wilting, which is likely a result of the chosen limits on h_A.

The resulting lack of sensitivity of many of the simulations to drawdown could be a result of the system geometry. A simulation of the equilibrium matric potential, that is the matric potential that would occur when the soil water is in equilibrium with the water table, shows that all the areas are well above stressed conditions (Figure 19). This also indicates the strong potential for upwards water flow of saline water towards the soil surface, given the strong atmospheric demand for water. It also illustrates the strong control that soil texture will have on water retention. As a result, failure to account for movement of salt from the saline groundwater upwards into the soil has the potential to cause predictive error.

4.6 Plant Physiological Modelling

Plant water use is a sink term in the model and is parameterised according to the Feddes stress function, with no salinity stress and a spatially discretised root density distribution. The Feddes function describes the relative changes in the potential root water uptake as a function of matric potential. A special modification to HYDRUS is also used in order to simulate two plant types with different Feddes parameters, and different spatially distributed root distributions. In addition the use of an option to allow plants to preferentially uptake water from wetter areas of the unsaturated zone, termed Compensated Root Water Uptake, is also discussed in the following.

4.6.1 Static and Robust Vegetation

There are currently several major limitations to modelling of plant water consumption using HYDRUS. When considering longer term dynamics the first of these limitations is that vegetation is not dynamic. For example, even after an extreme drought plant water use would immediately return to peak levels if soil moisture returned to optimal levels, whereas one would expect a delayed response due to mortality and senescence (e.g. Scott et al., 2006). As a result, HYDRUS may predict higher rates of transpiration during droughts in response to intermittent rain events and potentially drier soil conditions, with the potential to overestimate the likelihood of reaching wilting point. It is for this reason that great care must be taken in assessing impacts to plants and resilience to altered hydrology when using HYDRUS and other models that do not account for the dynamics of below and above ground biomass.

In addition, HYDRUS does not consider the dispersal of seed, establishment of juvenile plants, growth and eventual death of individuals. The samphire vegetation shows distinct spatial organisation that appears to result from episodic recruitment related to flooding of the Marsh, specific requirements by seeds for establishment and the death of plants in areas of historical flooding/drying. HYDRUS cannot simulate changes in the spatial organisation of plants without significant user intervention through repeated re-initialisation of the simulation. While this is beyond the scope of the Report, understanding the dynamics of recruitment and establishment in relation to the hydrology of the Marsh may be relevant for understanding the resilience of these communities to hydrological disturbance.

4.6.2 Water and Osmotic Stresses

The Report used experimental data collected by UWA (Figure 12 in the Report) to estimate the parameters of the Feddes water stress function governing the rates of potential uncompensated root water uptake. The data were apparently plant physiological measurements made in soils with salt solutions of varying concentration and as such represent total soil water potential, i.e. the sum of osmotic and matric potentials. More information on the experimental methodology needs to be presented in the Report in order to be able to properly interpret the results of these experiments.

As the report claimed the DoubleVeg version of HYDRUS was unable to simulate salinity stress it was argued that converting the results to matric potential would be sufficient for modelling purposes. The documentation of DoubleVeg however suggests salinity stress can be simulated. In addition, reports suggest that the samphire plants are some of the most salt tolerant species known yet there is a salinity impact upon transpiration particularly at the highest concentrations tested (English and Colmer, 2013). Nevertheless, despite their high salt tolerance this does not justify omitting the osmotic potential from calculation of the total potential as it is still a component of the energy potential required to be overcome in order for the plant to take up water from soil. Neglecting the osmotic effect means that the occurrence of permanent wilting could be under predicted by the modelling.

Using the UWA experimental data the Report estimated Feddes parameters by converting the total water potential, using the osmotic potentials of soil water extracts into the matric potential using Equation 7 of the Report i.e.:

$$h = \emptyset + 102.5\frac{\theta_s}{\theta(h)}$$

where h is the matric potential, ϕ is the measured total water potential, θ_s is the soil porosity, $\theta(h)$ the volumetric soil water content and 102.5 is an estimated osmotic potential derived from a groundwater salt concentration of 18000 ppm. The choice of such a high default concentration is to make the values of the matric potential at wilting point and optimum point much higher (less negative) than they probably are in reality.

It is not clear how the above equation was derived as there are no references to justify it. The osmotic potential of a liquid does not depend upon the water content. However, the rational may be that as a soil dries the salts remain in the soil and therefore the concentration increases proportionally. This should be stated if it is the case.

In addition, it is not clear where values for the unsaturated volumetric water content were obtained from, as they are not documented. It is also not documented how the total water potential was measured as this may have a bearing on its interpretation for use in Equation 7. Was it measured in situ, i.e. in the soil or in the plant? If concentrations of extracts and the volumetric data was available then it should be possible to collapse many of the points in Figure 12 of the Report onto a common curve to better estimate the Feddes parameters.

At first the approach seems to be a conservative one and could enhance the likelihood of simulating the occurrence of wilting point. However, the choice of a wilting point as occurring in the middle of the scatter of points rather than at the upper (less negative) end of points is a less conservative approach. It actually suggests that 50% of phenotypes are unaccounted for by the modelling. In fact the Water Stress Reduction Coefficient first becomes zero for water potentials ~600 m H2O less negative than the adopted permanent wilting point.

4.6.3 Compensated Root Water Uptake

Compensated root water uptake is described as the ability of a plant to utilise water where it is located in the soil and not necessarily on limited to what proportion of its roots are located there (Jarvis, 1989). For example if a proportion of a plant's roots were located in a wet area and the rest in dry soil then the plant could adjust the spatial distribution of its uptake to meet the evaporative demand. This readjustment, or weighting, is termed compensated uptake and has support from experimental studies on plant water use (Jarvis, 1989; Green, et al., 2006; Javaux et al., 2008). There are several published applications of modelling compensated root water uptake as well as theoretical development (Skaggs et al., 2006; de Jong van Lier et al., 2008; Jarvis, 2010). In nearly all applications of either 1-D, 2-D or 3-D modelling of unsaturated water flow and compensated root water uptake a single plant is considered (e.g. Šimůnek et al., 2009; Deb et al., 2013). In the few others that consider multiple plants the system is reduced to a largely one-dimensional problem with little spatial variation.

In the spatially distributed cases, i.e. 2-D and 3-D applications, there are specific reasons why modelling of compensated root water uptake with HYDRUS focuses on single plants. This is because HYDRUS has no way of distinguishing the root zones of one plant from that of another, unlike the spatially distributed modelling in McGrath et al., (2012) for example. Compensated root water uptake adjusts the spatial weightings of the root water uptake term over all roots irrespective of how far apart they are. HYDRUS makes no distinction in the root zone that a particular sink term of a node (the roots in HYDRUS) belongs to one plant or another. Hence why application to large areas and many plants has not been considered previously.

As an example of the potential consequences we could examine circumstances similar to those assessed in the Report. Consider, a gently rising hill, 1 km in length. Plants cover the entire hill with a fixed rooting depth but limited in extent, say 3 metres in all directions. The water table is flat, as in the proposed model. At one end the deepest roots are close to the water table and able to access the capillary rise in the unsaturated zone. At the other end, the deepest roots are 5 m above the water table with limited access to water from groundwater. During a prolonged period with no rainfall, the modelled total evapotranspiration could be maintained at high levels due to the access to water by the roots at the lower end, near the water table. Compensated root water uptake would enhance demand at the bottom of the hill and supress it at the top of the hill in order to meet the evaporative demand. At the same time, plant roots at the top of the hill could conceivably be in soil with matric potentials below wilting point. In addition the average matric potential over the whole root zone could be above permanent wilting. Therefore, model simulations have the potential to wrongly suggest that the plants across the whole model domain are transpiring well and that they have access to sufficient soil moisture. In addition the compensation reduction in demand at the top of the hill would also lower rates of decline in soil moisture and thus also reducing the potential for the occurrence of permanent wilting.

A possible solution is to reconsider the need for a 2-D model in the first place. It is not clear from the results presented whether there is any significant lateral redistribution of water in the unsaturated zone. There currently is the potential for this to occur at the layer boundary between the loam and clay loam. However, it is not known how significant this is.

A basic simulation test of a similar but simplified geometry was conducted to assess this. The same soil properties and depths were used and the system allowed to come to equilibrium, i.e. no flow which was then used as the initial condition (see Figure 19). Then 200 mm of water was applied over two days and the results evaluated for 900 days thereafter with no more atmospheric forcing. The results show that the clay loam layer impeded water flow and saturation of the upper loam layer occurred (Figure 20). However, even in these circumstances the dominant flow direction was downwards due to the low hydraulic conductivity of the soils simulated. Although, there was likely a significant contribution to downward flow by the constant head lower boundary, as evidenced by the high vertical fluxes at the lower end of the hill, where near complete saturation of the profile occurred.

An inspection of the initial conditions, which appear to have been derived from some simulation, also suggests there is little evidence for significant lateral flow effects as can be seen in the spatial variation in matric potential (see Figures 8 to 18).

4.6.4 Possible osmotic effects on compensated root water uptake

The results of isotopic sampling of Marsh plants indicated that at the time the plants were accessing shallow soil water of meteoric origin and were avoiding using water at depths below 60 cm (Equinox, 2013). These results occurred just months after a significant rainfall event, Tropical Cyclone Heidi. However, sap flow measurements conducted from 2008 to 2011 suggested the samphire species adopted a conservative water use strategy, rather than an opportunistic one, with low rates of transpiration sustained during prolonged dry periods. These two observations suggests that the plants may selectively source water throughout the profile, preferring fresher water, yet are able to uptake water in moderately saline conditions during drier periods without significant impacts upon transpiration rates.

There is the potential that by neglecting osmotic effects on soil water retention the model is incorrectly simulating the temporal changes in the source of water for the plants. Fresh water from rain pulses could have less negative water potential than saline groundwater and thus a compensated uptake mechanism could account for preferential consumption of water from Tropical Cyclone Heidi and other intense events, before returning to a steady and conservative consumption of more saline waters. Therefore, even without the addition of a salinity stress to the Feddes uptake function, salinity impacts upon compensated root water uptake could help explain spatial patterns of root water uptake.

It is mentioned in the report that in the DoubleVeg version of HYDRUS it is not possible to simulate salinity stress with the Feddes function, however the DoubleVeg documentation specifically mentions where to include the salinity stress parameters in the input file for the second vegetation type. Alternatively, the 1-D version of HYDRUS could be applied, albeit with differing water table elevations to represent different positions along the hillslope.

5 Conclusions and Recommendations

On the basis of the uncertainty surrounding the experimental stress data, as presented, it is recommended that in a revision of this report there is a more comprehensive description of the experimental data and methodology. This will allow better interpretation and critique of the derived stress function and its parameterisation.

Observational evidence suggests the osmotic potential may be regulating the spatial patterns of water uptake from soil that is currently not simulated. It is recommended that there be some consideration of temporal changes in salinity by the modelling to account for water uptake patterns. As this has flow on effects for the rest of the water balance it may be important to consider. This could be done via the inclusion of a salt and its transport in HYDRUS, which may require parameterisation from measurements on field samples prior to implementation in a numerical model.

The calibrated maximum potential transpiration coefficient, Kcb, should be increased manually toward the observed maximum. The current calibration under predicts peak transpiration rates. The comparison of modelled to observed rates further suggests that there are soil hydraulic, and/or water/salinity stress limiting transpiration during the dry season that is currently not being simulated correctly.

Simulation of compensated root water uptake appears to be required to model plant water use at this site, however it currently cannot be simulated properly at the spatial scales as implemented in this model. The inherent limitation is the inability of HYDRUS to simulate the water use and resulting compensated water uptake of individual plants. Currently the compensation occurs over the entire spatial domain, wherever there are roots. In this case even the DoubleVeg version of HYDRUS, which is capable of simulating two plant types, is conducting compensation over several hundreds of meters for each plant type, however in reality root water compensation only occurs at the scale of individual plants.

As an alternative it is recommended that 1-D simulations could be considered, as there was no evidence produced of significant lateral water flows through the saturated or unsaturated zones. Initial modelling of a simplified landscape with similar soil properties and boundary conditions, conducted for this review, suggests that lateral subsurface flows are small in comparison to vertical flows. The use of 1-D simulations would provide better characterisation of water consumption patterns as impacted by salinity, as well as the likelihood of experiencing wilting. In addition a broader range of soil characteristics could be assessed. The lack of a sensitivity analysis to soil properties is a significant limitation of the current modelling effort, given only one mix of soil types was assessed and the wilting point is expected to be sensitive to soil texture. If 2-D simulations are considered necessary then an alternative model should be considered, whereby the water uptake of individual plants can be simulated.

There is the opportunity to utilise existing groundwater bore data to calibrate alternative soil hydraulic properties and to describe an alternative lower boundary condition that may better capture the observed variation in groundwater levels at the site. In addition a field study to assess the spatial variability of unsaturated soil hydraulic properties would provide useful data for model parameterisation. A better lower boundary could demonstrate the robustness of water recharge to the root zone via upwards water flow from episodic large rain events.

The assumed impact of canopies upon potential soil evaporation rates is far from being conservative. Despite the likely overestimated canopy interception, soil evaporation appears to be underestimated in this modelling exercise. It is recommended that the potential soil evaporation rates be adjusted upwards, possibly based upon measured values from the field. Other non-conservative assumptions should be reviewed as well, including the temporal resolution of modelled rainfall, and higher than observed root properties both shallow in the profile and at depth.

The final recommendation is not specifically related to the modelling but to the observation that there exists a sharp vegetated boundary on the fringe of the Marsh, that may be an indicator of episodic recruitment and plant establishment, as well as natural death events, not just the medium term dynamics of the unsaturated zone. Such patterns likely arise as a result of specific flood characteristics, post-flood rainfall and natural drought events permitting seedling germination, growth to maturity and death. Understanding how and when these events occur will significantly contribute to the interpretation of the resilience of the samphires to short term dewatering.

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7 Figures

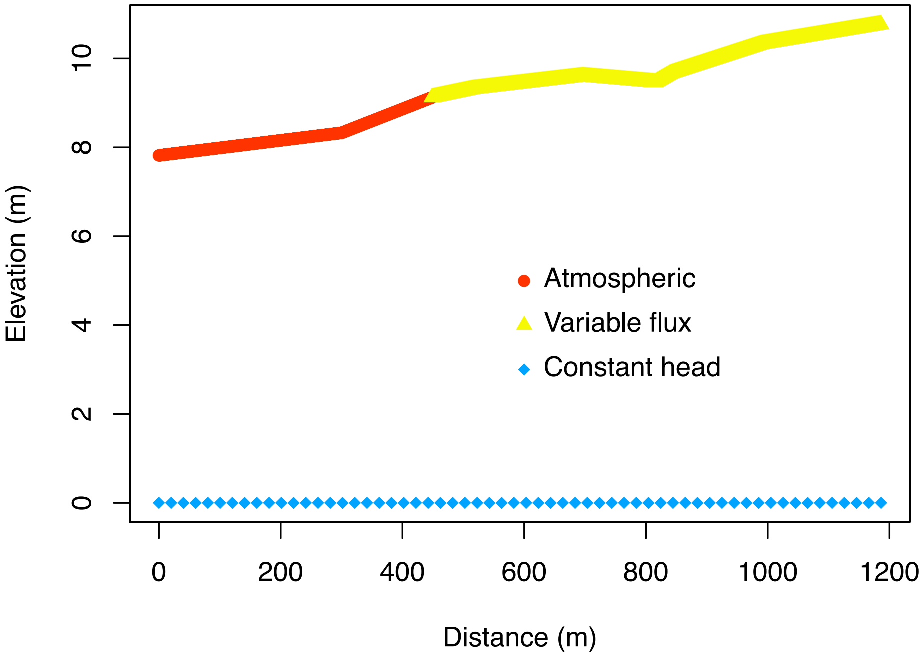

Figure 1: Boundary types as extracted from simulation DDN1Dry.

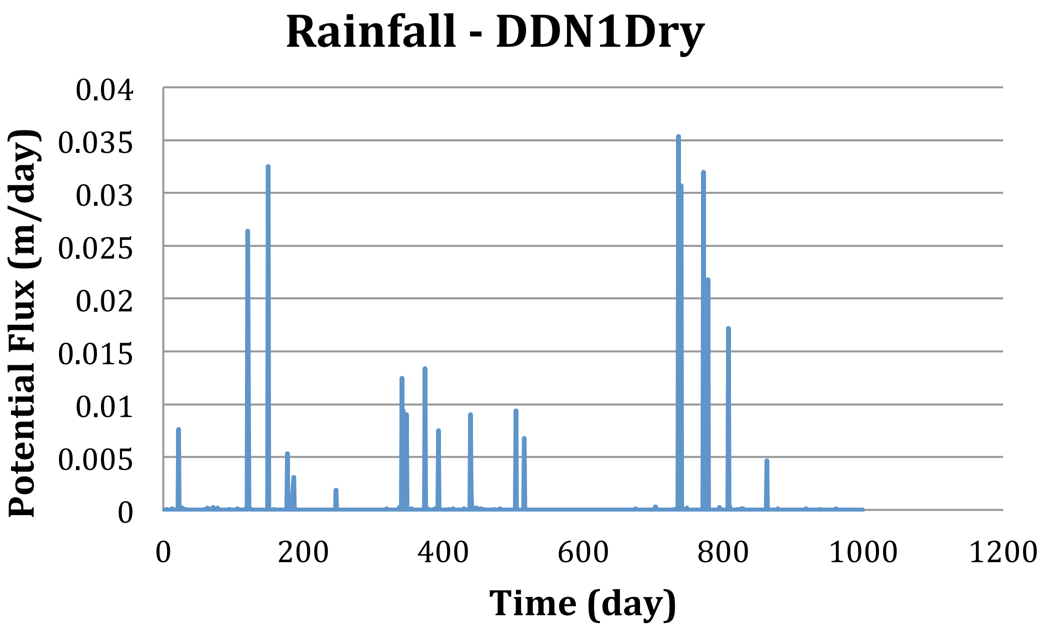

Figure 2: Simulated rainfall for DDN1Dry.

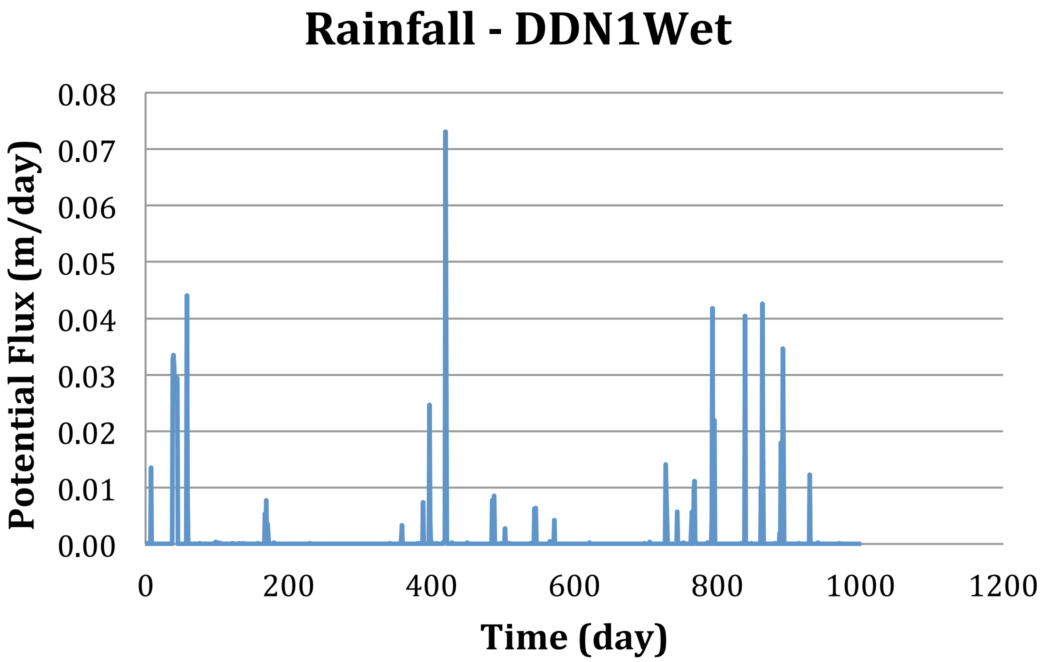

Figure 3: Simulated Rainfall for simulation DDN1Wet.

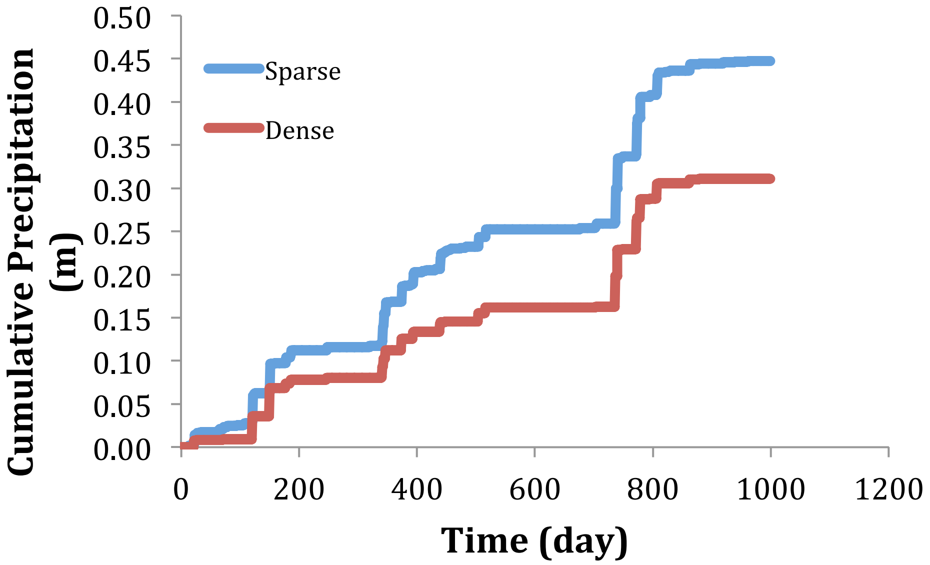

Figure 4: Difference between simulated effective precipitation between Sparse and Dense zones for the simulation DDN1Dry.

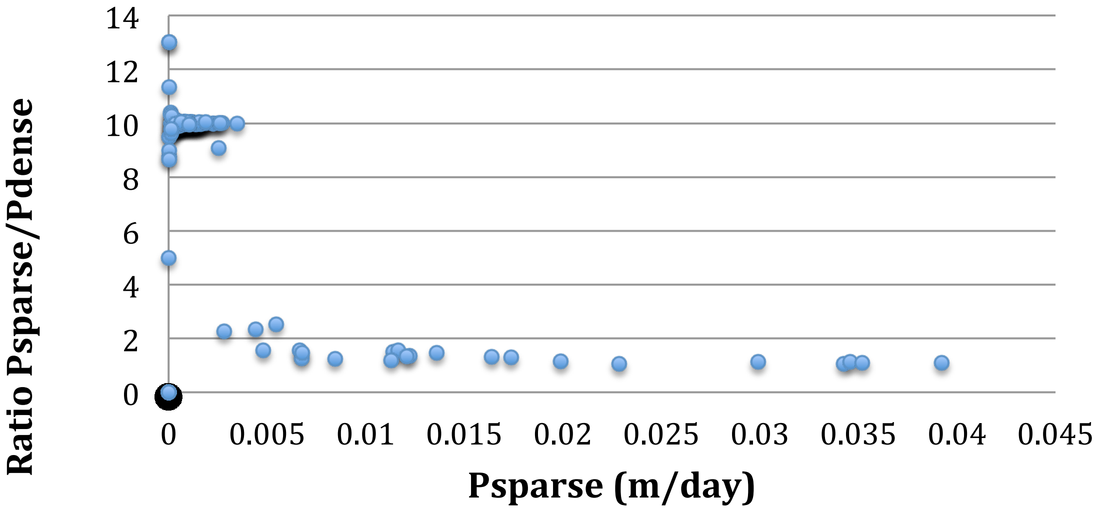

Figure 5: Ratio of effective precipitation in the Sparse zone to that in the Dense zone.

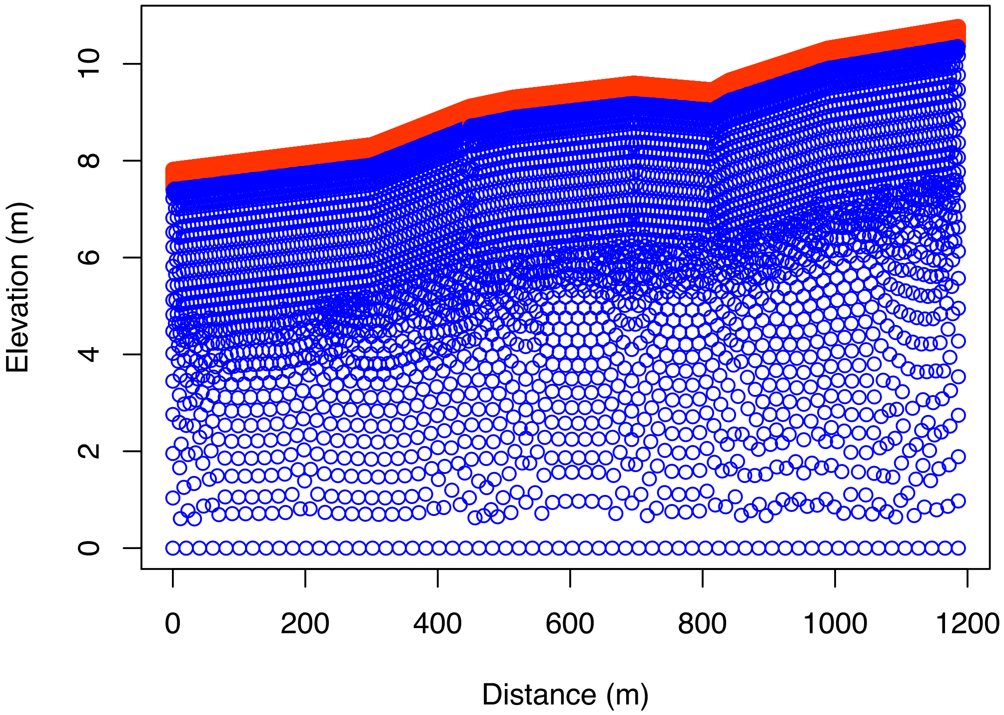

Figure 6: Spatial distribution of the nodes of the finite element mesh and the distribution of soil properties. Loam (red) and clay loam (blue).

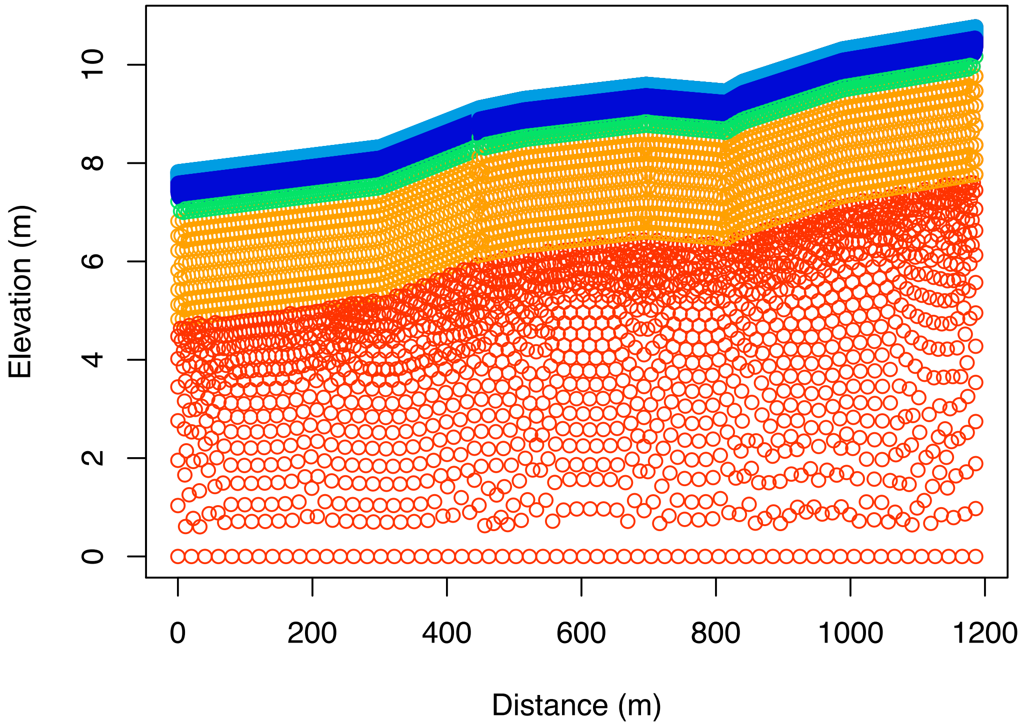

Figure 7: Distribution of root water uptake potential at the finite element nodes of the model. Highest to lowest potential is indicated by the colours dark blue (0.8574), light blue (0.6984), green (0.5641) then orange (0.1464). Red (0) indicates no root water uptake. Data extracted from simulation DDN1Dry.

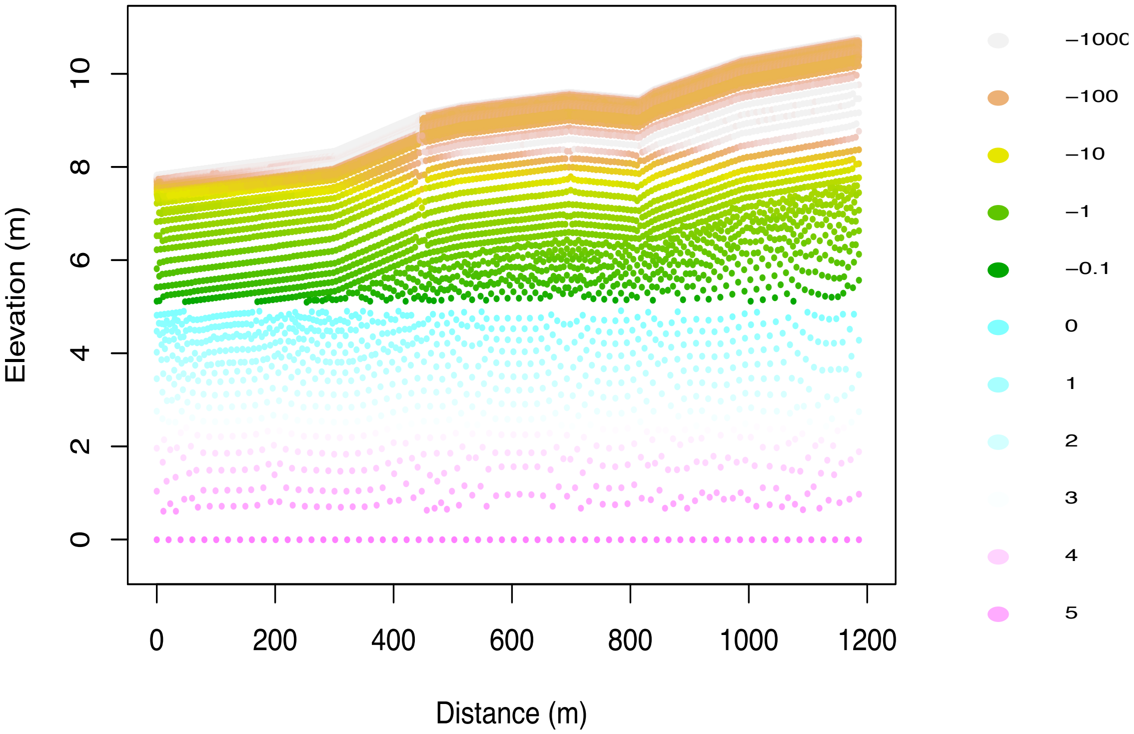

Figure 8: Initial pressure head at nodes of the finite element mesh from DDN1Dry. Green –brown – grey indicates decreasing (more negative) matric potential (i.e. decreasing soil moisture) in the unsaturated zone. Units are m H2O. Blue – white – pink indicates increasing pressure head from 0 m to 5 m H2O (i.e. increasing depth below the water table).

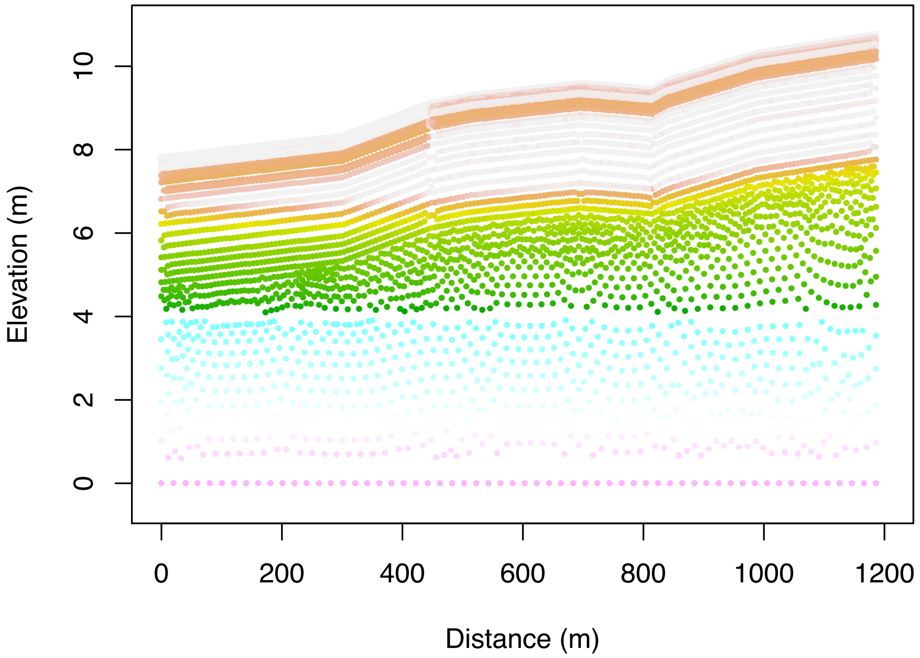

Figure 9: Initial head at nodes of the finite element mesh from simulation DDN2Dry. Colour scale as in Figure 8.

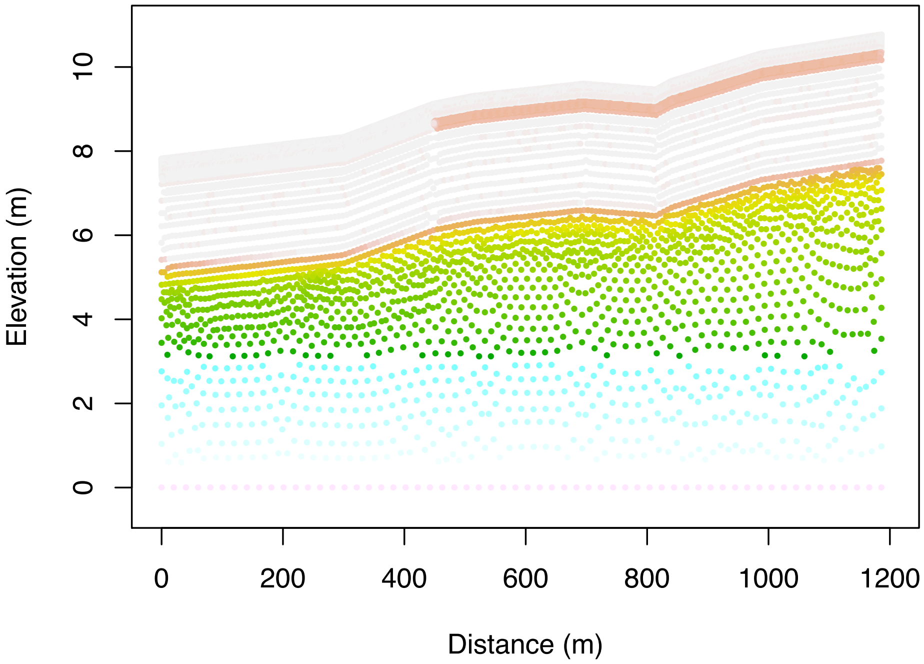

Figure 10: Initial head at nodes of the finite element mesh for simulation DDN3Dry.

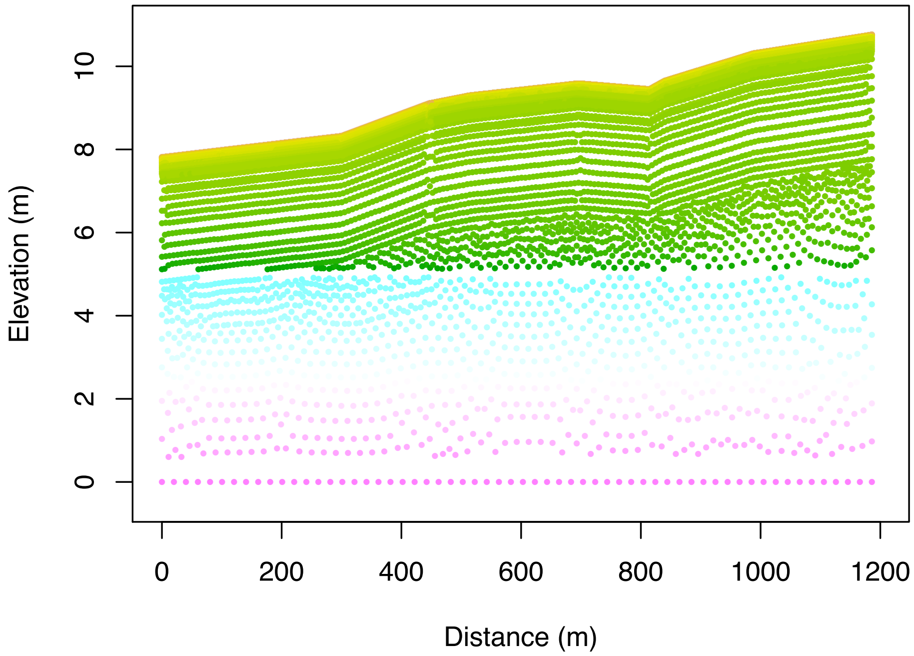

Figure 11: Initial head at nodes of the finite element mesh from simulation DDN1Wet.

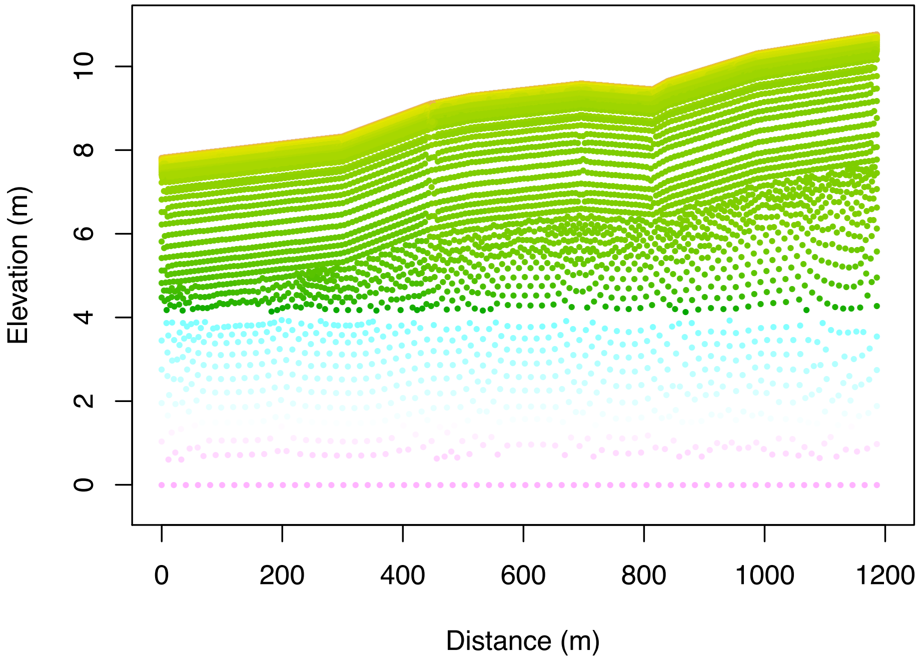

Figure 12: Initial head at nodes of the finite element mesh from simulation DDN2Wet.

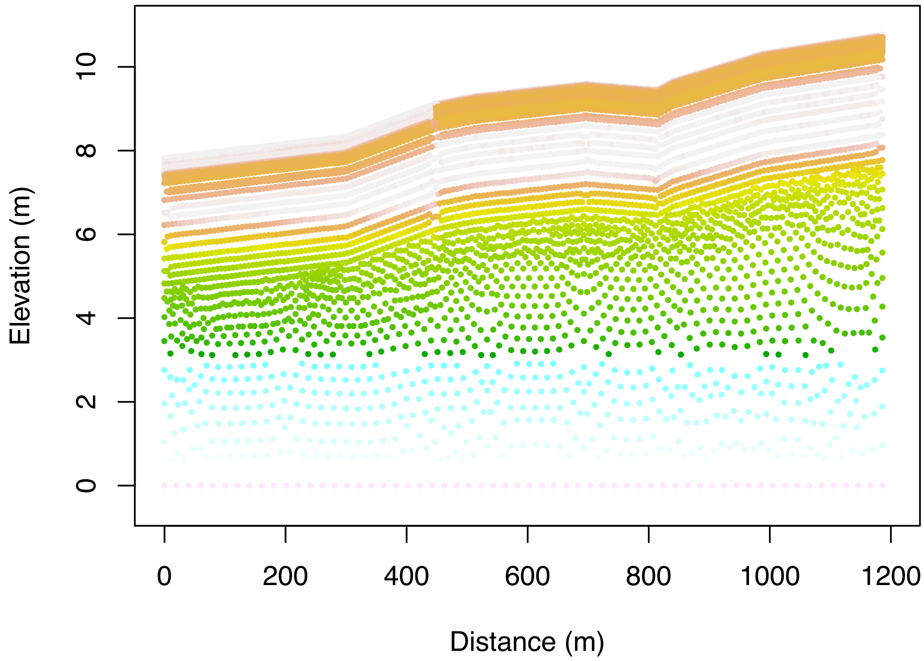

Figure 13: Initial head at nodes of the finite element mesh from simulation DDN3Dry_nonCompen.

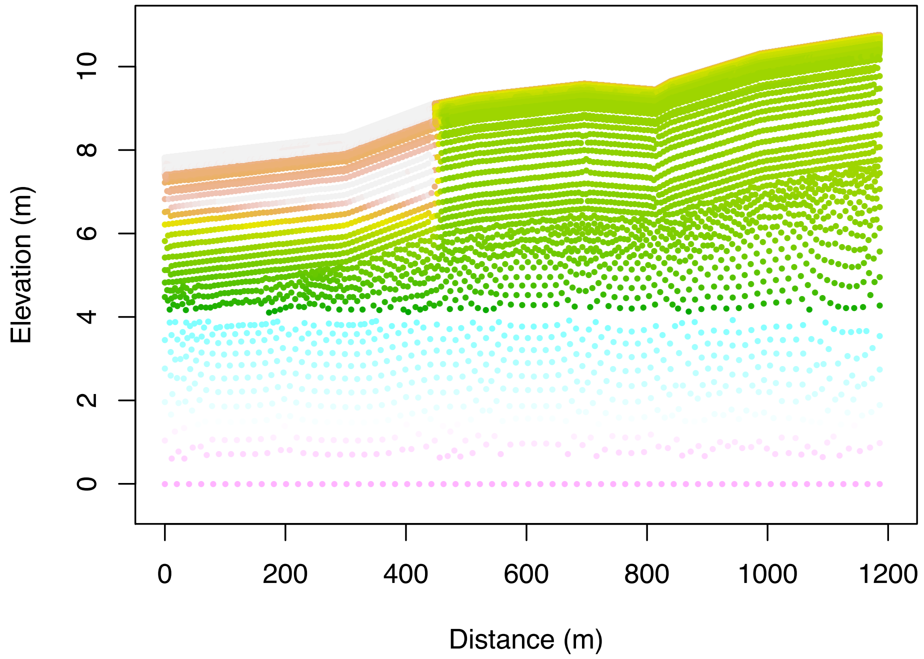

Figure 14: Initial head at nodes of the finite element mesh from simulation DDN2DrySparse.

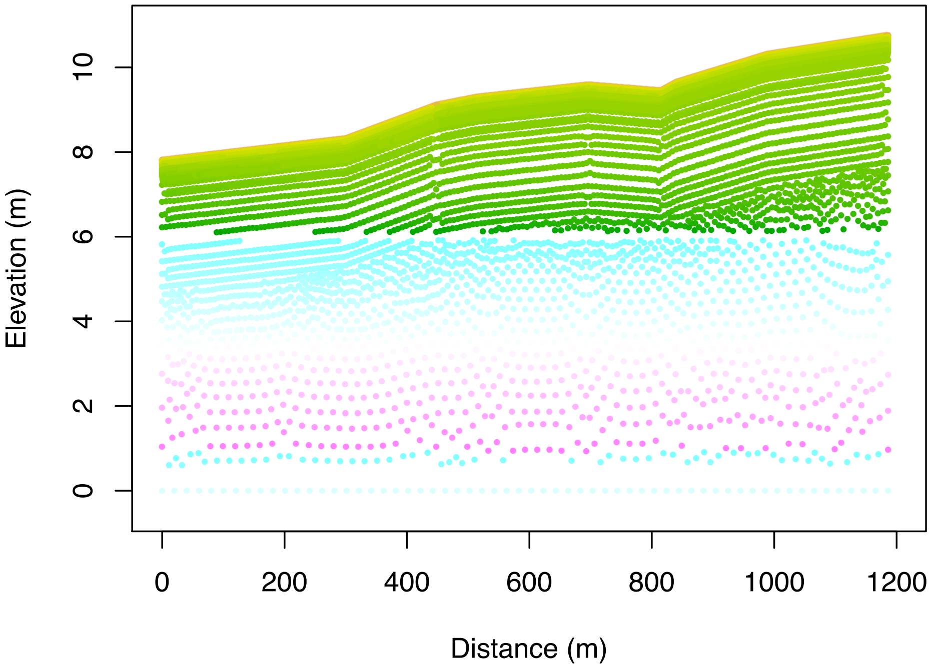

Figure 15: Initial head at nodes of the finite element mesh from simulation kcbCalib.

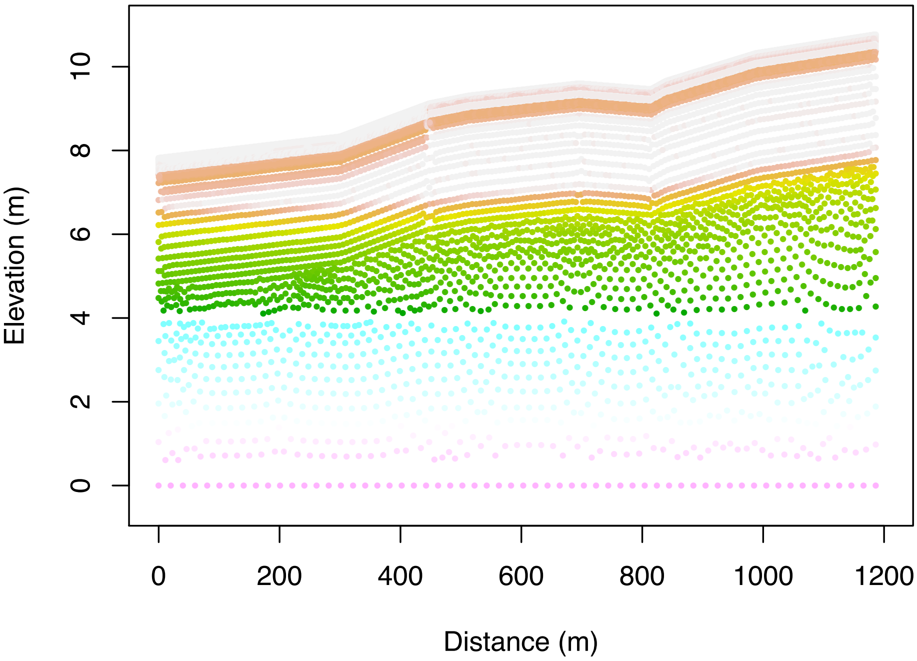

Figure 16: Initial head at nodes of the finite element mesh from simulation DDN2Dry1_5static.

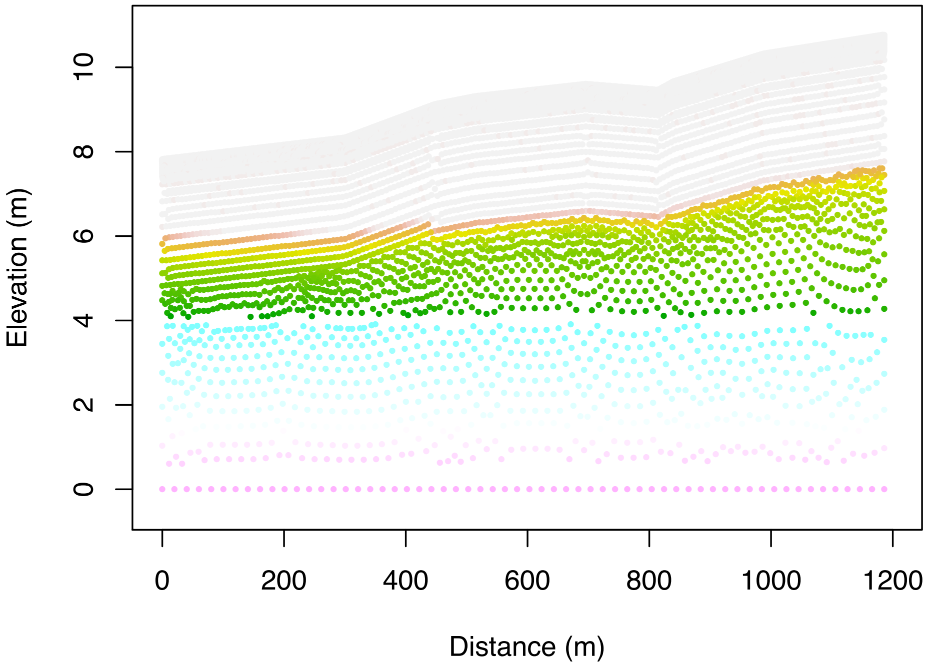

Figure 17: Initial head at nodes of the finite element mesh from simulation DDN2Dry1_5kcb.

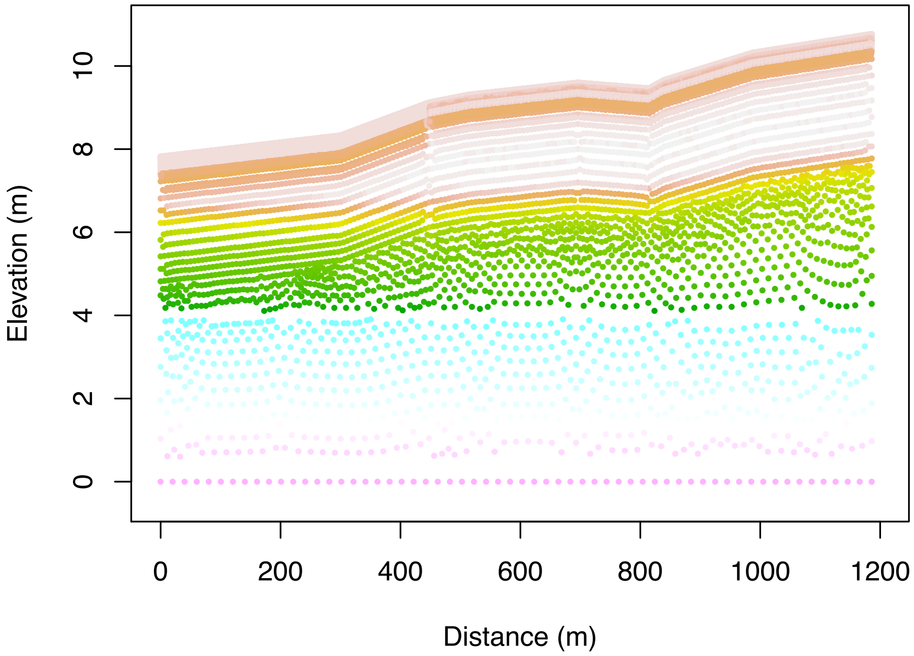

Figure 18: Initial head at nodes of the finite element mesh from simulation DDN2Dry7MPa.

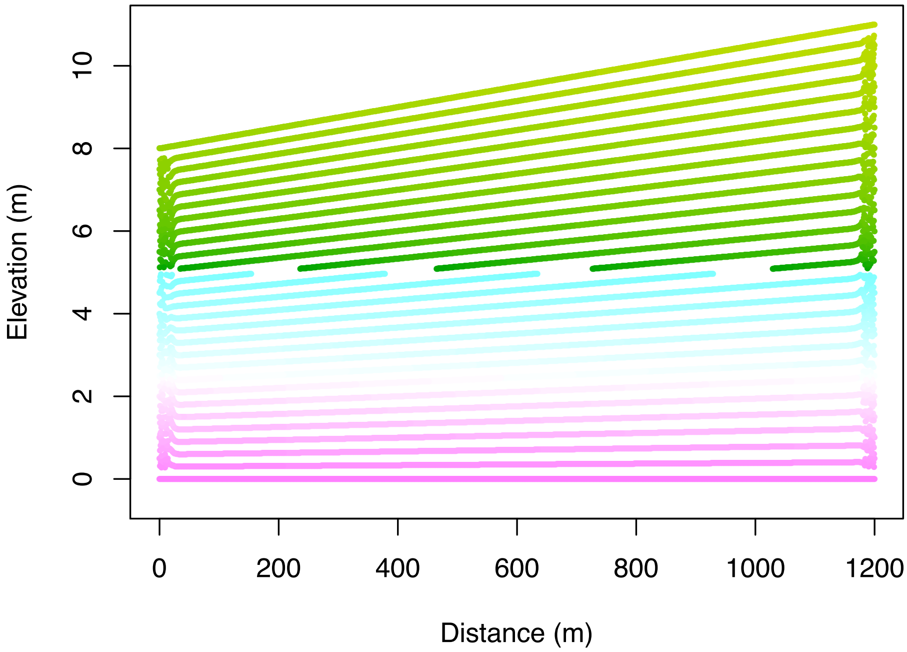

Figure 19: Equilibrium matric potential in a model system with similar geometry to the modelled domain.

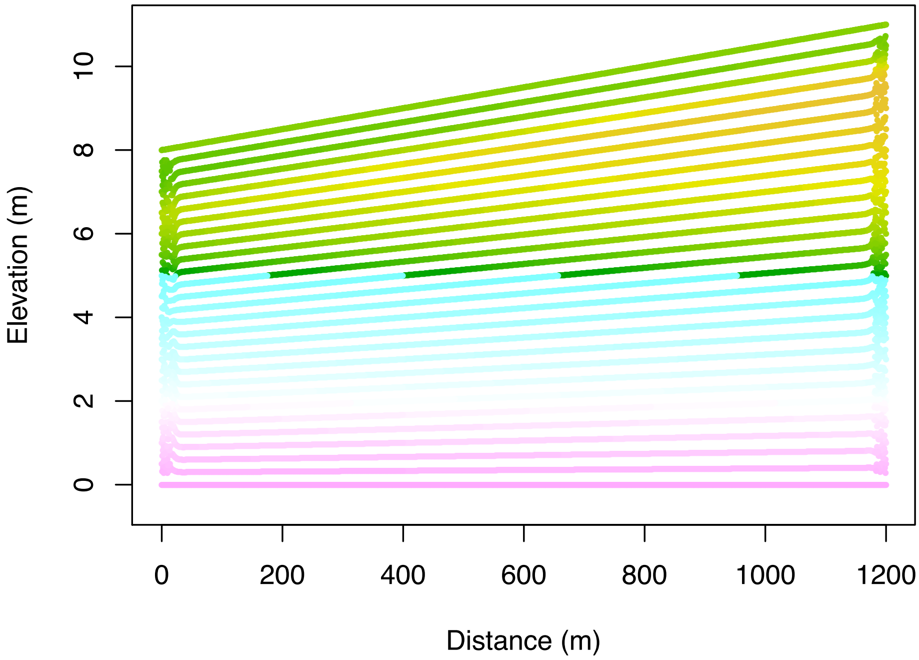

Figure 20: Simulated matric potentials in a model system 10 days following a simulated 200 mm rain event.