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ENGINEERING DOCUMENT

PROJECT REPORT

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NUMBER	PREP-1200-G-12638/C
DESCRIPTION	SELECTION PHASE STUDY EASTERN PILBARA REGION SURPLUS WATER PROJECT CREEK DISCHARGE MODELLING REPORT
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ACRONYMS AND ABBREVIATIONS

Acronym/abbreviation	Definition
1D	One-dimensional
2D	Two-dimensional
3D	Three-dimensional
AEP	Annual Exceedance Probability
AHD	Australian Height Datum
ARR2019	Australian Rainfall and Runoff 2019 (Ball *et al.,* 2019)
BoM	Bureau of Meteorology
BWT	Below water table
DEM	Digital Elevation Model
DPS	Definition Phase Study
DMIRS	Department of Mines, Industry Regulation and Safety
DWER	Department of Water and Environmental Regulation
EPG	Eastern Pilbara Grid
EPRSW	Eastern Pilbara Regional Surplus Water
ER	Eastern Ridge
FY	Financial year
HT	Level vs time
L/s	Litres per second
k	Coefficient of permeability / hydraulic conductivity
k_h	Vertical hydraulic conductivity
kL	Kilolitre
k_v	Horizontal hydraulic conductivity
LiDAR	Light Detection and Ranging
MGA	Map Grid of Australia

Acronym/abbreviation	Definition
EP	Eastern Pilbara
ML/d	Megalitre per day
m/d	Metre per day
mm/d	Millimetre per day
mm/h	Millimetre per hour
m^3/s	Cubic metres per second
OB18	Ore Body 18
OB31	Ore Body 31
PSD	Particle size distribution
SGS	Subgrid sampling
SPS	Selection Phase Study
QT	Flow vs time
WAIO	West Australia Iron Ore

1 EXECUTIVE SUMMARY

BHP Iron Ore Pty Ltd (BHP) engaged Worley to undertake project management and engineering works for the Selection Phase Study (SPS) component of the Eastern Pilbara Regional Surplus Water (EPRSW) Stage 1 project.

[redacted] Additional scopes of work relating to wetting front estimation for various test pumping discharge scenarios for Caramulla Creek were identified to support and improve the outcomes of the overarching EPRSW project.

[redacted] The wetting front models were developed with the TUFLOW Heavily Parallelised Compute (HPC) software package and calibrated based on the discharge trial and streamflow data provided by BHP, to refine the conceptualisation and parameterisation of interflow layers of 2D TUFLOW models.

Several scenarios were simulated to estimate the length of wetting front propagation downstream following the release from the proposed discharge locations for [redacted] test pumping sites. [redacted] It was found that the wetting front associated with the proposed test pumping would reach between 0.9 and 3.7 km after 150 days, depending on the exact location and discharge rate.

Net recharge to groundwater was calculated using recorded streamflow data to serve as a reference point for the infiltration parameters adopted in the wetting front modelling. Results suggest a net creek infiltration rate in the order of 0.3 m/year between the Caramulla Discharge and Downstream flow gauges.

Sensitivity analyses explored how variations in relevant parameters affect the predicted wetting front for creek systems. The variations in hydraulic conductivity, initial moisture and depth to clay showed that the estimated wetting front distances were sensitive to these parameters. Changes to initial moisture and depth to clay were found to affect the wetting front distance more so than altering the hydraulic conductivity of the soils (within plausible parameter ranges).

2 INTRODUCTION

2.1 Project background

BHP Western Australia Iron Ore (WAIO) operates a number of iron ore mine sites within the Eastern Pilbara (EP) region of Western Australia. Surplus water generated from below water table (BWT) mining activities is managed via the integrated EPRSW Management System servicing Eastern Ridge (ER), Mt Whaleback, Ore Body 18 (OB18), Ore Body 31 (OB31), and Jimblebar.

Surplus water within the EP region is forecast to increase from 100 ML/d in FY22 to >300 ML/d in FY30 due to the growing reliance on access to BWT ore deposits. Currently there is insufficient surplus water management capacity to enable the optimal mine plan for the above assets.

Creek discharge modelling to estimate the timing and extent of the potential wetting front(s) associated with various discharge scenarios and locations is therefore required to support WAIO environmental and heritage evaluation and approvals processes.

[redacted]

[redacted]

2.3 Project scope

[redacted] The modelling aim was to estimate the extent of surface water inundation along the creeks and take into account progressive mounding of groundwater from surface water infiltration through the base of the creeks. Discharge trial and/or streamflow data was used to calibrate model parameters, where available.

Test injection bores are to be constructed by BHP at various locations within the Caramulla and Thirteen Creek floodplains to inform the design of a Managed Aquifer Recharge (MAR) scheme. A total of fifteen new test injection bores are planned (eight in Caramulla East and seven in Thirteen Creek). All injection bores will require test pumping, and during this testing water will be discharged to natural drainage.

For this purpose of the wetting front modelling study, a total of six discharge locations have been selected, generally located on drainage lines. The locations are summarised in Table 2-1 and shown on Figure 2-2. Locations have been selected to allow a spatial comparison of the wetting front extent from various points, generally being as far upstream and within tenure as practical. [redacted]

Sensitivity analyses were also conducted to explore how variations in relevant parameters affect the predicted wetting front for the Caramulla Creek systems. Estimation of the net recharge to groundwater from surface water infiltration based on recorded streamflow data was also required.

Table 2-1: Proposed test pump discharge locations (coordinates in MGA51)

Name	Comment	Easting	Northing
01_Thirteen	On 13 Creek flow channel - Furthest point upstream and within tenure	242,040	7,409,647
02_Thirteen_ unnamed	Unnamed 13 Creek central drainage line, up stream	241,324	7,412,407
03_Thirteen_ unnamed	Unnamed 13 Creek far west drainage line, up stream	237,802	7,411,533
01_Car_East	Caramulla northern area - no channel	232,499	7,413,281
02_Car_East	Caramulla southern area - no channel	234398	7,411,009
03_Car_East	Caramulla southern area - minor possible channel	230,178	7,410,542

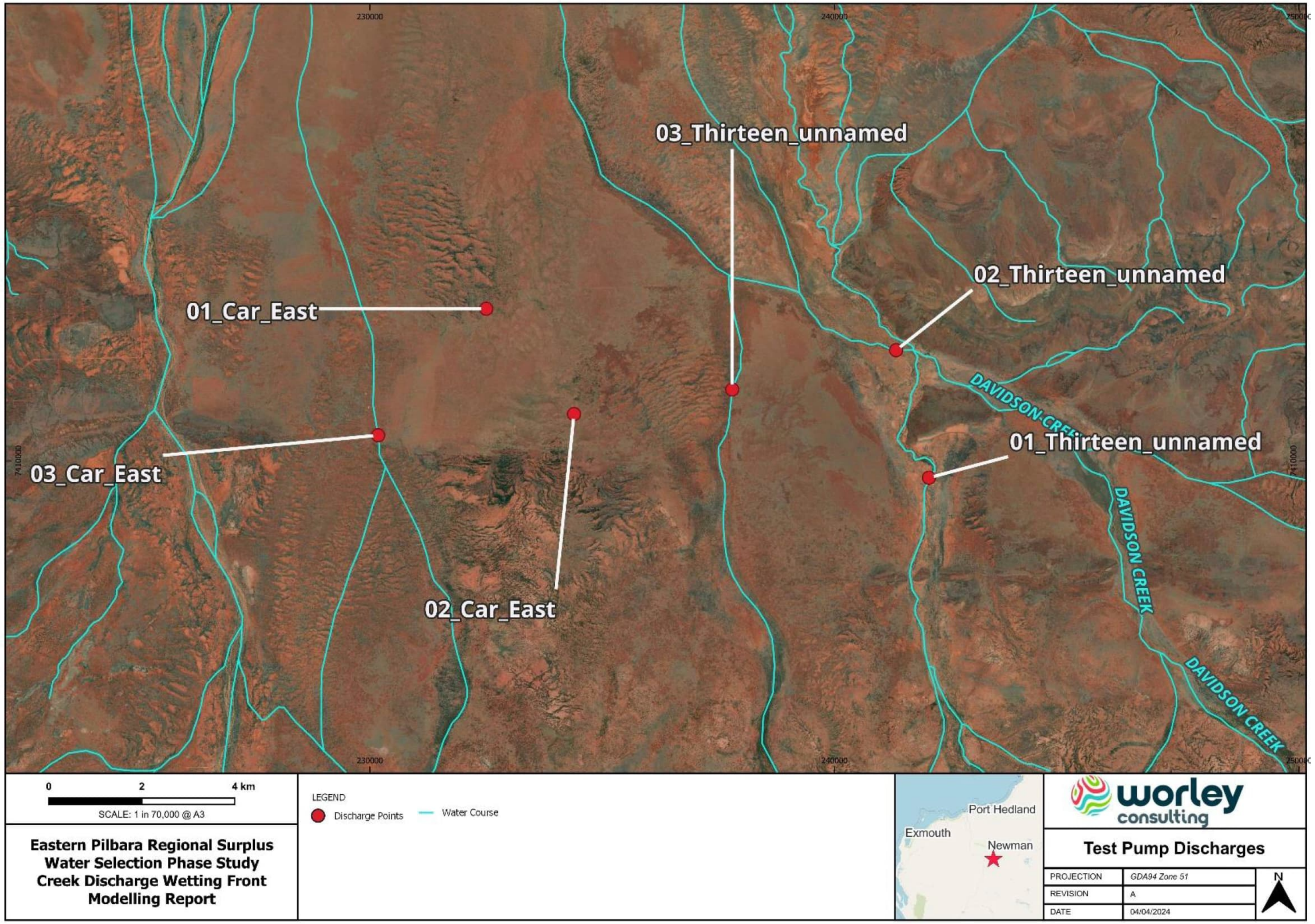

Figure 2-2: Modelled test pump discharge locations.

2.4 Purpose of report

The purpose of this report is to describe the methodology and assumptions adopted in the development of the 2D TUFLOW models and summarise the results with regards to the estimated timing and duration of the wetting front associated with various creek discharge points.

This includes discussion on the calibration of parameter values used for the predictive wetting front modelling for Jimblebar Creek, and the estimation of net groundwater recharge based on recorded streamflow data to provide a reference point for the infiltration rates applied in the TUFLOW model.

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[redacted]	[redacted]
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[redacted]	[redacted]
[redacted]	[redacted]
[redacted]	[redacted]
[redacted]	[redacted]
[redacted]	[redacted]

Surface geological maps were obtained from the Department of Mines, Industry Regulation and Safety website (DMIRS, 1989). The 1:250,000 scale map shown in Figure 2-3 indicates the presence of extensive alluvial sediments, colluvium and aeolian sands in and around the flow paths of the three creeks in question.

The 1:500 000 regolith map of Western Australia Regolith of WA (DMIRS, 2018) presented in Figure 2-4 was used to inform the assumptions regarding the unconsolidated sediment thickness in the 2D TUFLOW model.

The topographic survey data listed in Table 2-2 was used to generate digital elevation models (DEMs) needed for the creek discharge modelling. Figure 2-5 shows the extent of DEM coverage for Jimblebar Creek, Caramulla Creek and Thirteen Creek. The consolidated DEM shows ground elevations varying from 400 to 615 m AHD.

Other sources of data referred to over the course of the study included the following publicly available reports:

- *FerrAus Pilbara Project Environmental Impact Assessment* (Strategen, 2012),
- *Robertson Range Dewatering Study* (Aquaterra, 2008), and
- *Davidson Creek Preliminary Mine Dewatering Analysis* (Aquaterra, 2009).

3 SURFACE WATER MODELLING

2D modelling of surface and near surface (alluvial) flow was carried out using the 2023-02 release of the TUFLOW HPC software package. This release includes a layered interflow feature to simulate cumulative infiltration into up to ten distinct subsurface layers, and to model horizontal advection and vertical transmission within and between the subsurface layers (BMT, 2023), referred herein as interflow.

It is noted that this interflow functionality is not intended to replace detailed groundwater modelling, but rather provide a quasi-3D mechanism that can more accurately represent the flow of water through a creek system when compared to a pure 2D model. This simplified approach was deemed suitable due to the paucity of site-specific groundwater data over much of the creek areas that were being modelled.

Details pertaining to the conceptualisation of this process and how it is modelled in TUFLOW can be found in the release notes (https://downloads.tuflow.com/TUFLOW/Releases/2023-02/TUFLOW%20Release%20Notes.2023-02-AA-Beta3.pdf).

3.1 Modelling approach

The low number of semi-permanent and permanent water features located in the study area indicate that it is a relatively dry area typical of the ephemeral creek systems found in the Pilbara, most of which are likely to be intermittent and dependent on rainfall and shallow alluvial interflow.

The modelling considered the near-surface geology of the creeks to include constraints relating to the available water storage and flow within the subsurface strata and alluvium of the creek systems. These constraints and characteristics were approximated based on available data and assigned to the subsurface layers under the creek channel in the model domain.

A key component of the modelling approach included developing and calibrating a 2D model for Jimblebar Creek with reference to:

- The measured wetting front extent resulting from discharge trial events undertaken by BHP;
- The revised regolith thickness data informed by the Loupe survey conducted in November 2023 (SGC, 2023);
- Geological drill hole data around Jimblebar, Caramulla and Thirteen Creek used to validate the revised regolith thickness data.

“Regolith thickness” in this case refers to the thickness of unconsolidated sediments in the modelled alluvial system. It is a proxy used in absence of detailed information typically obtained from exploration drilling.

“Interflow” in this report represents the intermittent shallow subsurface flow within the modelled alluvial system associated with the release of discharge.

[redacted]

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[redacted]

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[1] It is noted that BHP have since collected discharge trial data from Caramulla Creek, which should be used in future project phases to refine the parameterisation of the wetting front model.

3.3 Cell size

The 2D model base cell size was set to 20 m (with sub-grid sampling resolution of 1 m) to strike a balance between practical model run-times whilst still providing acceptable results. Sensitivity testing assessed the effect of adopting a smaller base cell size (10 m), and the differences in results were found to be negligible. Given the considerable increase in model runtimes associated with the 10 m base grid size, it was decided to adopt a 20 m base grid size.

Sub-grid sampling (SGS) extracts elevation data from an underlying DEM which is typically at a finer resolution than the model base cell size to develop a non-linear relationship between the water surface elevation and the cell's volume when calculating the cells' storage capacity.

SGS also generates a non-linear relationship between the water surface elevation and the cell face area and cell width (or wetted perimeter) to improve the representation of the fluxes across the cell. The SGS approach continues to compute a single water level for each cell, but the computations to determine the cell volume and cell face fluxes utilise the higher resolution terrain data. Figure 3-2 provides a schematised presentation of SGS (Huxley, et al., 2022).

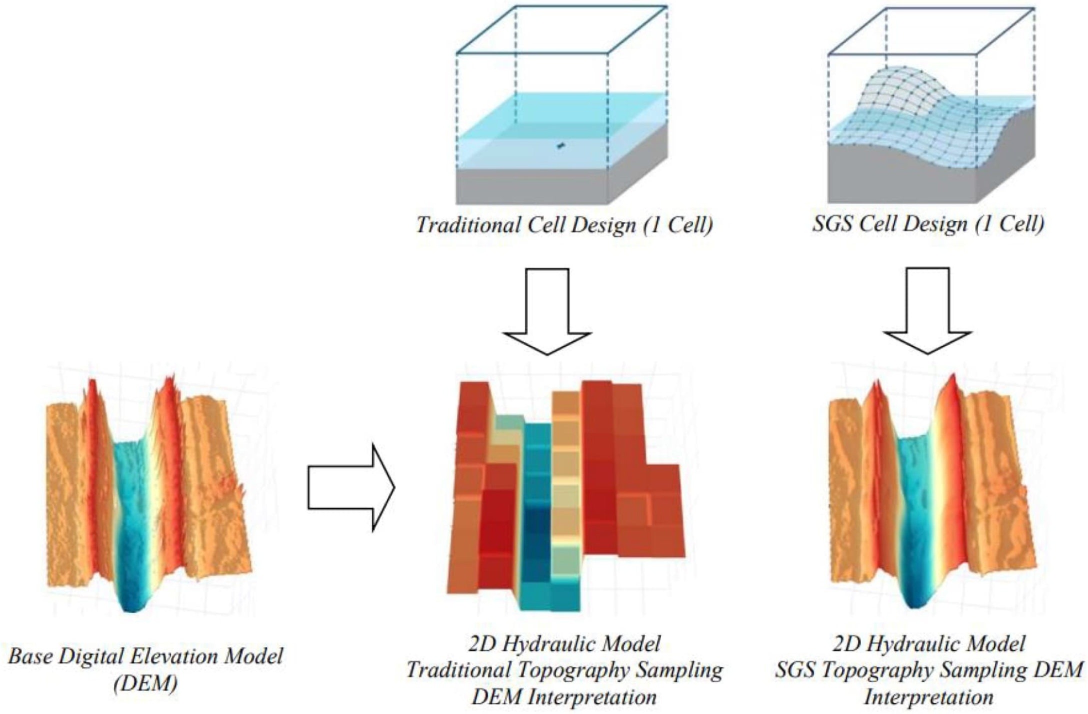

Figure 3-2: 2D Topography sampling concept (Traditional vs SGS) (Huxley, et al., 2022)

3.4 Boundary conditions

Boundary conditions define the volume/rate of flow entering and exiting the model. All inflow boundary conditions were assigned a QT flag, defining the boundary condition to be set in a flow vs time format (prescribed flux). All downstream boundary conditions were assigned a HT flag, defining the format of the boundary condition to be water head vs time (prescribed head).

Several boundary conditions were applied as listed below:

- The inflow boundary conditions associated with various surplus water discharge locations were implemented as source area polygons within the 2D model domain.
- The outflow boundary condition was applied at the downstream end of the model to allow water to exit the model in the event that it reached the end of the model domain.
- Evaporation was represented as the negative rainfall. Further detail regarding this is provided in Section 3.4.1.

Natural rainfall/runoff processes were not considered as part of the modelling.

3.4.1 Evaporation and evapotranspiration

Bureau of Meteorology (BoM) data indicate that the average areal annual evapotranspiration in the vicinity of Newman is around 300 mm, with the average areal potential evapotranspiration being around 1,500 mm per year.

A value of 8.5 mm/day for evaporation was deemed appropriate for the direct evaporation from the creek discharge, as the reduction factor and the pan-to-lake coefficient is applicable to large water bodies, whereas the width of the discharge stream is likely to be of the order of the size of the pans used for recording evaporation.

There are also temperature effects for pan evaporation measurements which may also reduce the evaporation experienced by the creek discharge. It is understood that the surplus water is likely to be piped to the discharge location, therefore the temperature of the water may be equivalent to the temperature in the Class A pan used for evaporation measurements.

An appropriate evapotranspiration rate for the creek alluvium would be larger than the average areal annual evapotranspiration (300 mm) as the average includes upland areas, where the water table is deep and the evapotranspiration is negligible or zero. Based on the available data, the creek channels within the TUFLOW model domain have comparatively shallow depth to water table (ranging from 4-15 m bgl), and thus evapotranspiration will be larger than the annual areal average in these areas. Areas outside the creek channels have higher depth to groundwater (up to 45 m).

Evapotranspiration rate decreases with increasing depth to groundwater, a factor that cannot be readily implemented within the TUFLOW framework. Evapotranspiration rate was therefore conservatively averaged over the alluvial plain and outside of flowing stream.

Evaporation loss (8.5 mm/day) has been applied throughout the model domain for ponding water (including streams). This is similar to that in the Eastern Pilbara Water Resource Management Plan (BHP, 2018). This was applied as a negative rainfall in the TUFLOW model domain to simulate the evaporation and remove surface water from the model. If a negative rainfall is specified, it is treated as a loss in TUFLOW model. Negative rainfall is only applied to wet cells. As indicated, it is not possible to directly represent evapotranspiration from groundwater mounding along the banks of a stream in TUFLOW (along nominally dry cells).

3.5 Conceptualisation of interflow layers

In order to represent flow within the near surface strata below the creek bed to facilitate the interflow function in the TUFLOW models, a suitable selection of the below parameters was required for each layer:

- Vertical hydraulic conductivity (k_v)
- Horizontal hydraulic conductivity (k_h)
- Porosity
- Suction
- Initial moisture

A total of three interflow layers were incorporated into the subsurface of the TUFLOW models.

Table 3-1 lists the surficial hydrostratigraphical units found within the study area (based on existing geological and regolith mapping), and their respective parameter ranges. These ranges are based on values from RPS (2015) and previous experience with similar areas in the Pilbara.

Table 3-1: Surficial lithological units and suggested parameter ranges

Unit	Symbol	K_v (mm/h)	K_h (mm/h)	Porosity	Suction (mm)
Alluvium	Qa	12-42	125-416	0.1-0.25	200
Colluvium & minor alluvium	Qc	4-12	42-125	0.08-0.15	200
Colluvium & alluvium	Qw	8-42	83-416	0.1-0.2	200
Mixed lacustrine & aeolian deposits	Qd	4-17	42-167	0.05-0.15	200
Aeolian sand	Qs	8-17	83-167	0.1-0.25	200
Colluvium	Czc	2-4	21-42	0.07-0.12	200
Colluvium - partly consolidated/ consolidated	Czk	10-208	104-2083	0.05-0.5	100
Calcrete	Czb	2-4	21-42	0.07-0.12	200
Silcrete	Ho	0.004-8	0.04-83	0.001-0.05	200

3.5.1 Surface infiltration

An indicative vertical infiltration rate of 450 mm/day (18.75 mm/h) was proposed by BHP. This value was adopted as a starting point during preliminary simulations.

As another reference point, infiltration rates in the nearby Fortescue River during natural flow events were found be as high as 580 mm/day (I. Rea, 2021). It is noted that the flow area (and therefore the wetted perimeter) associated with a natural flow event is likely to be far greater than that associated with creek discharge flows. Thus, natural flow events have higher infiltration losses when compared to creek discharge flows.

The Green-Ampt infiltration loss model (Green & Ampt, 1911) was adopted in the TUFLOW models. It conceptualises the infiltration process as a ‘piston’ type with a well-defined vertical wetting front. As the infiltrated water moves in a vertical direction through the soil profile, soil moisture changes instantly from the initial content to a saturated state. When the infiltrated inflow is less than the saturated hydraulic conductivity, the soil moisture content reduces, and a period of soil moisture deficit recovery occurs. The Green-Ampt loss model was applied to the uppermost interflow layer only.

3.5.2 Estimated layer thicknesses

Thickness of the interflow layers was based on the available data characterising the underlying basement rock and overlying alluvium. The first interflow layer below the ground surface represented the upper portion of the vadose zone and was assumed to be 0.5 m thick.

The thickness of the remaining interflow layers was based on the interpretation of relevant bore logs and the recalculated regolith thickness grid “calibrated” on BHP-supplied Loupe data that covered Thirteen Creek.

The coverage of the Loupe data in relation to the Thirteen Creek model domain is presented in Figure 3-3. It covers a relatively small part of the modelled alluvium. These estimates would have to be confirmed by drilling in the future.

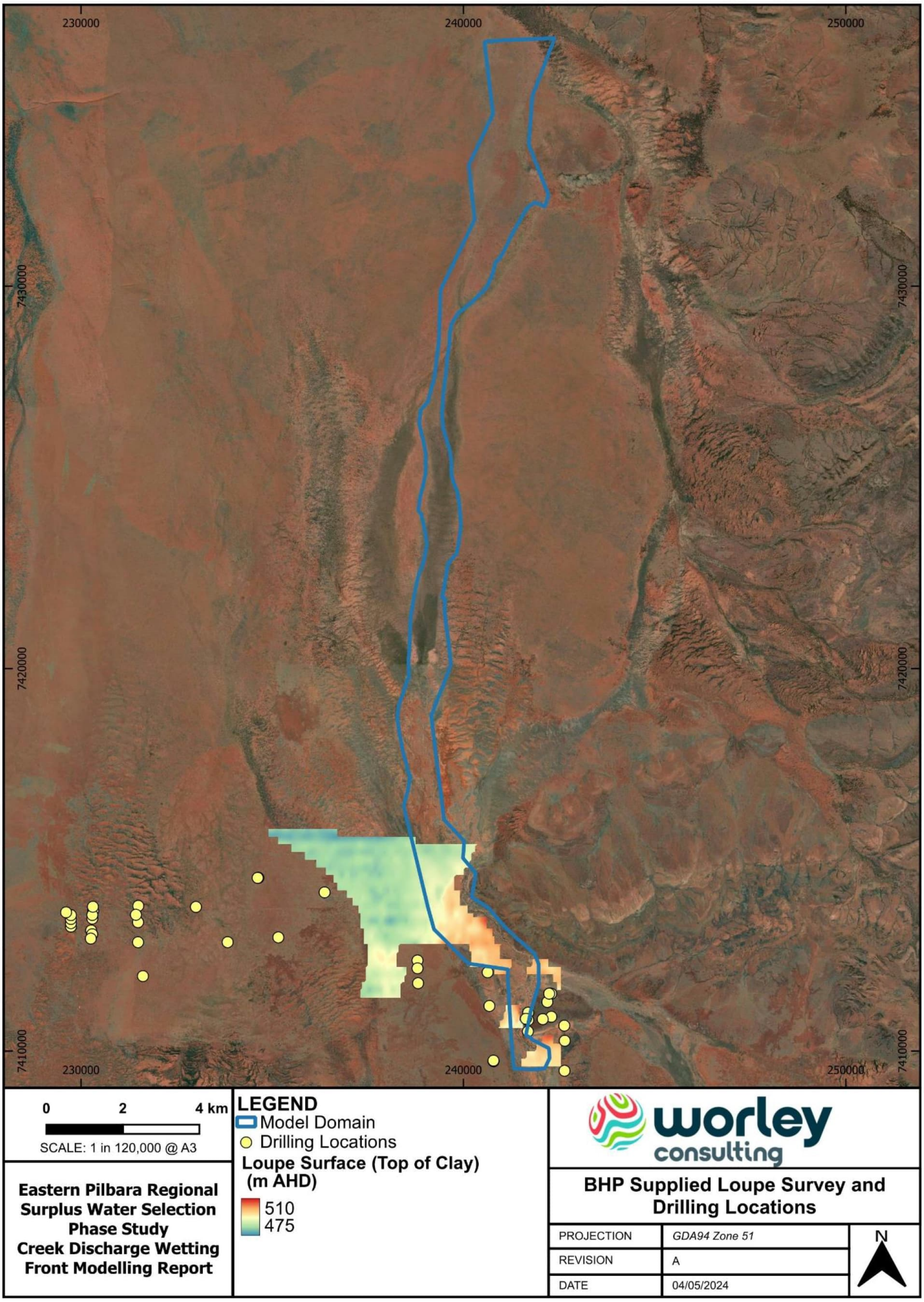

Figure 3-3: BHP-supplied Loupe survey data and bores

The following process was undertaken to adjust the regolith thickness data based on the geophysical Loupe survey:

- Using the Loupe clay surface as the reference surface, the regolith thickness grid was first compared and then adjusted using a statistical approach (multiplying/dividing and +/- the layer thickness to improve the fit). Figure 3-4 shows the elevation differences between the Loupe data and the original and adjusted regolith grids.

  The comparison process was performed manually and iteratively using Excel to determine the optimal combination of mathematical operators that gave the best outcome. The result uses the following derived relationship:

  $$Toc = \frac{(\mathrm{Rt} - 25.275)}{2} + 25.275$$

  Where *Toc* represents the depth to the top of clay, and *Rt* represents the regolith thickness (depth of regolith).

  A plan and cross-sectional view of the various surfaces are shown in Figure 3-5 and Figure 3-6 respectively.

- The process resulted in an average improvement of fit between the regolith thickness grid and Loupe surface by about 50% (i.e., elevation difference reduced by a factor of two).

- The recalculated regolith thickness grid was then compared against clay intersections identified from drilling data provided by BHP ("Drillhole Log - Extended.pdf"). The clay intersections were picked primarily where Al_2O_3 increased significantly, however other indications were also used. The adjusted regolith surface showed a good correlation with the clay intersections at most locations (Figure 3-7).

- The recalculated regolith thickness grid was then clipped to the TUFLOW model domain.

- The recalculated regolith thickness grid (m AHD) now no longer represents the base of the regolith, but instead represents the top of the clay horizon, as it was in effect "calibrated" to the Loupe data, which mapped the top of the clay horizon (i.e., conductive features). The validity of these correlations should be confirmed by future drilling.

The final interflow layer was used to represent the clay underneath the looser alluvial material.

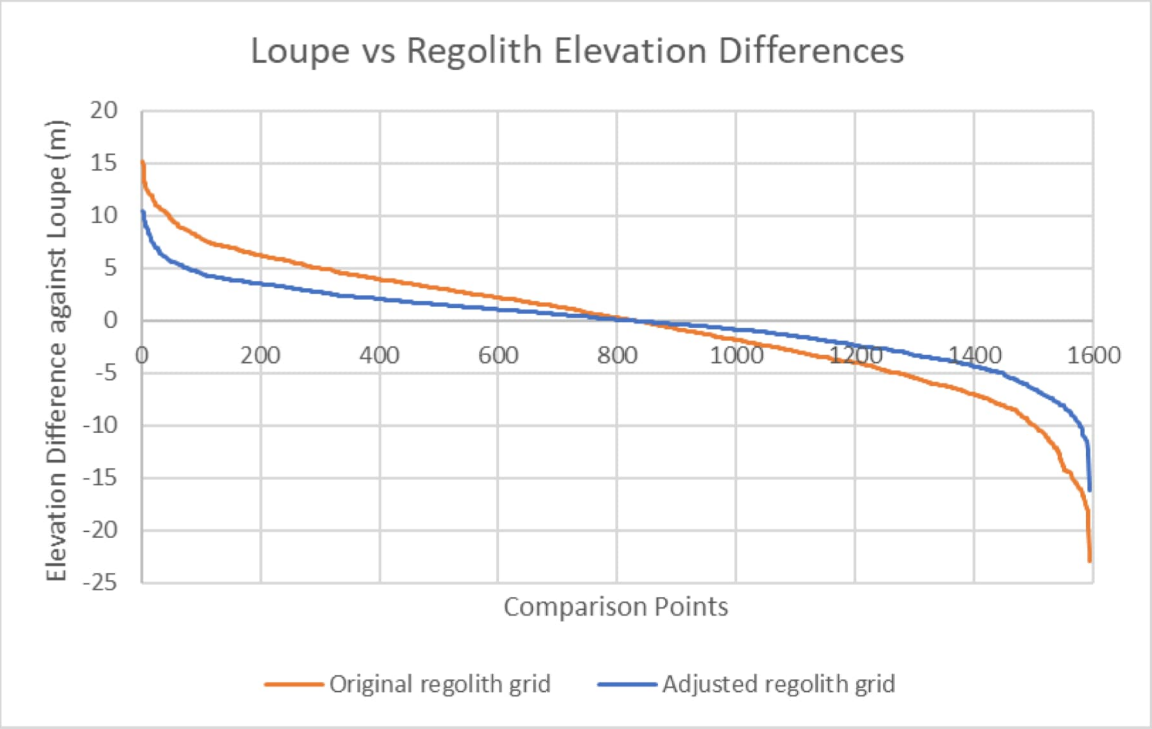

Figure 3-4: Elevation differences between the original and adjusted regolith grids, compared against the Loupe data

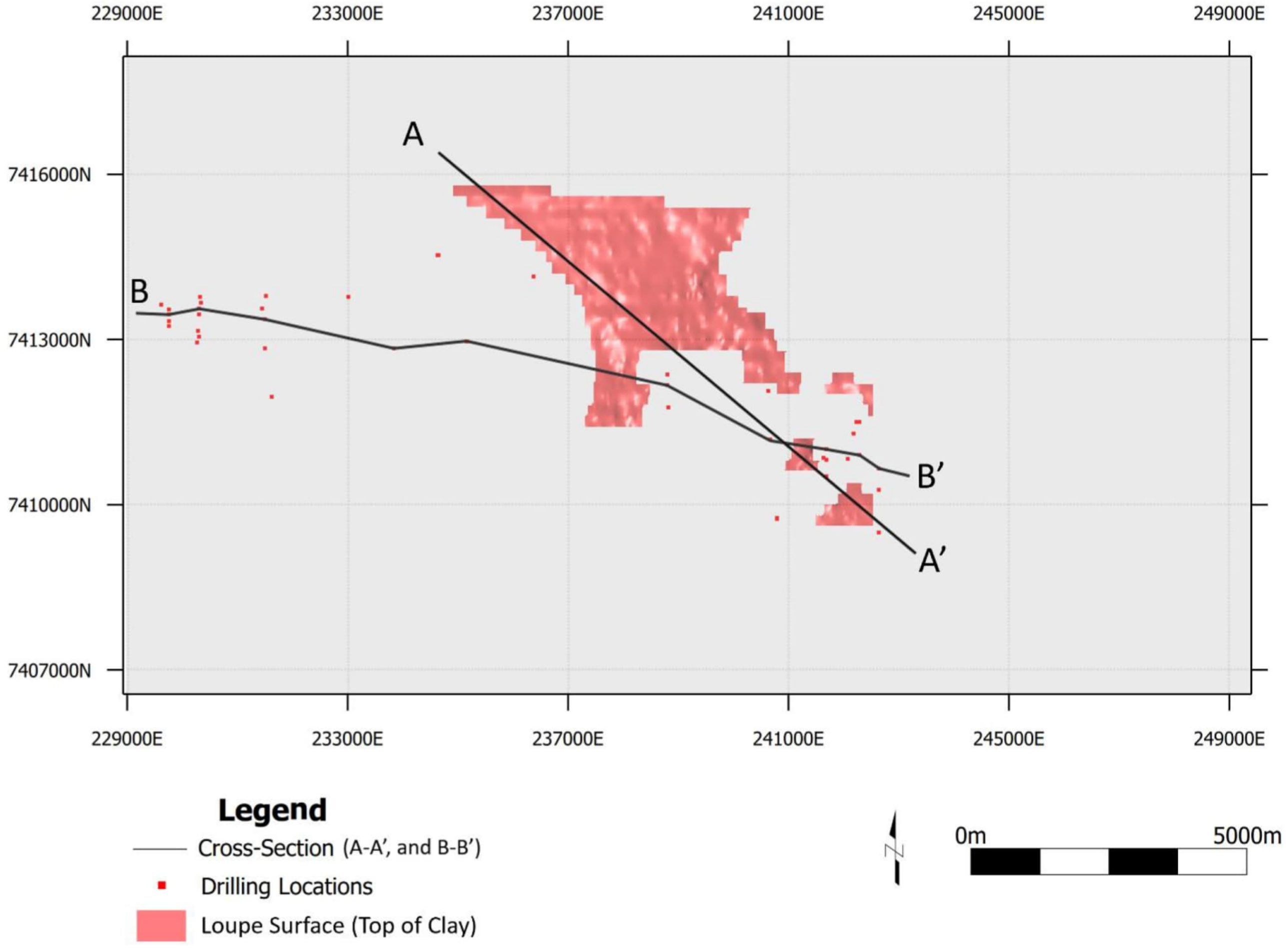

Figure 3-5: Plan view showing the location of cross-sections A-A' and B-B' with respect to the extent of the Loupe data and drilling locations

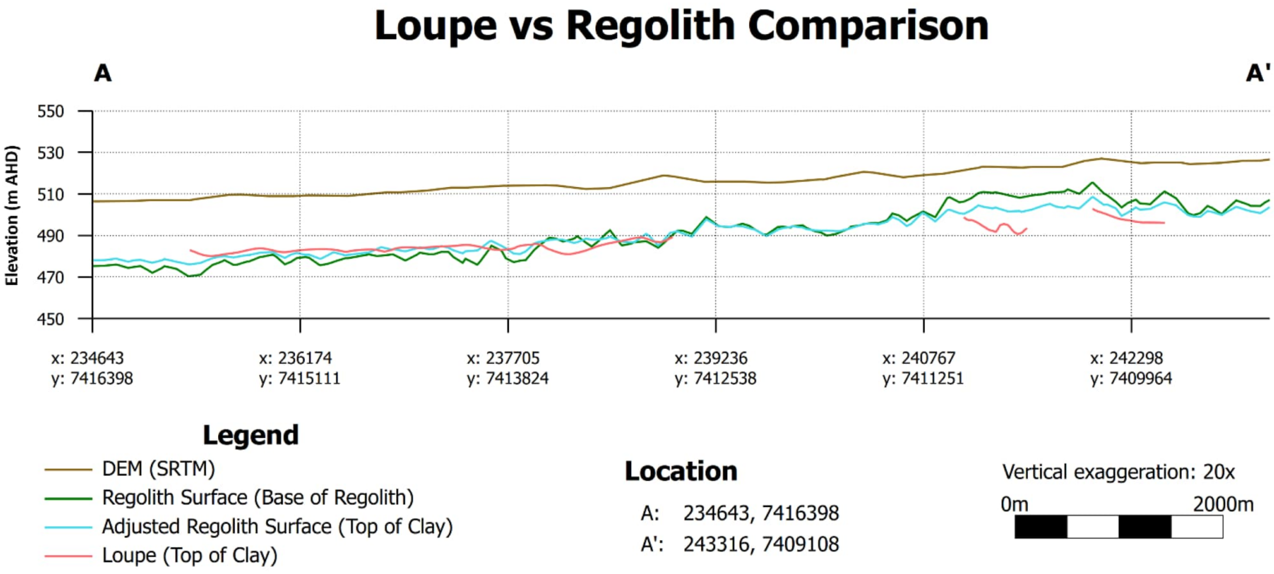

Figure 3-6: Cross-section (A-A') comparison of Loupe data with respect to the original and adjusted regolith surfaces

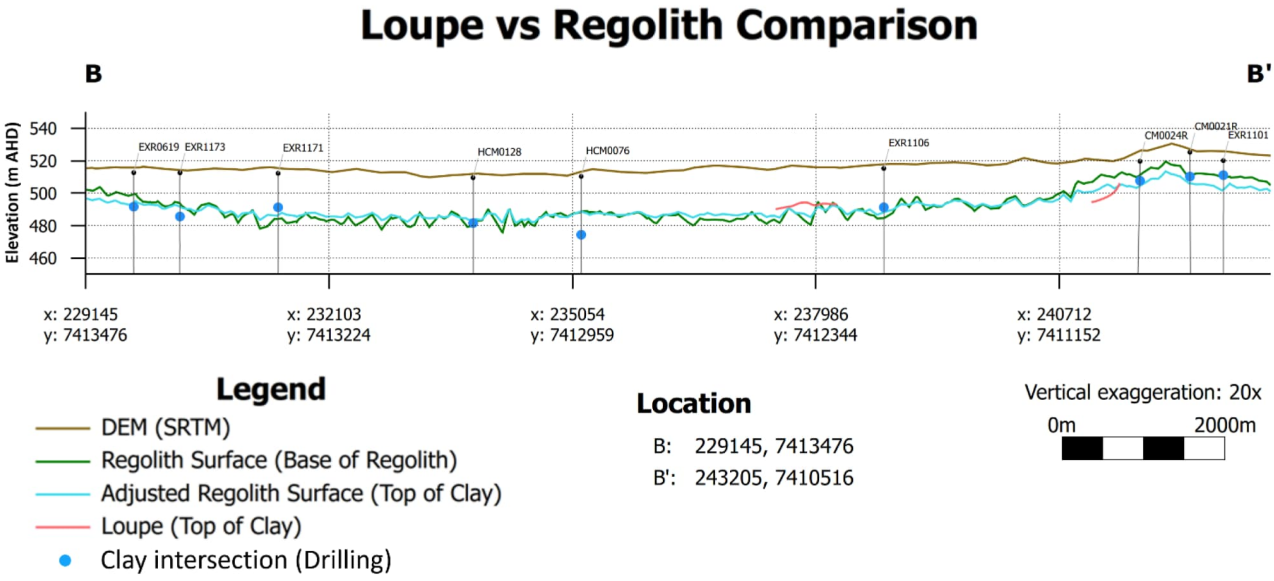

Figure 3-7: Cross-section (B-B') comparison of Loupe data with respect to the original and adjusted regolith surfaces and clay intersection from drilling

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3.7 Roughness

Manning's n roughness coefficient values were assigned in the TUFLOW model domains based on analysis of available aerial imagery. The following references were sought out in defining appropriate Manning's n values:

- Open Channel Flow (Chow, 1959)
- Recommendations in Australian Rainfall & Runoff 2019 (Ball et al., 2019)

Examination of the available satellite and aerial images indicated that there is a mixture of moderately and sparsely vegetated areas within the model domain. A depth-varying Manning's n was assigned throughout the domain, ranging from 0.1 for flow depths less than 0.05 m down to 0.04 for flow depths 0.5 m and deeper.

4 MODEL CALIBRATION

BHP conducted a discharge trial on Caramulla Creek, which ran from April to November 2022. Flow gauge data covering the period of this trial was provided by BHP, however, the flow gauges were unable to pick up the low flows associated with creek discharge. As such, it was not possible to conduct a model calibration using this data. It is understood that BHP have since installed more sensitive flow gauges which can record the low flows associated with creek discharge. It is recommended to revisit the model calibration for Caramulla Creek in the Definition Phase Study (DPS).

BHP conducted a separate discharge trial in an upstream reach of Jimblebar Creek over a two-month period in late 2022 and early 2023. The trial commenced at 9 am on 9 December 2022. The discharge rates and measured wetting front extent were used to calibrate the parameters (vertical hydraulic conductivity / infiltration rate, horizontal hydraulic conductivity, suction, porosity, and initial moisture) of the subsurface layers in the TUFLOW model.

Flow rate and volume was recorded by BHP and provided for use to calibrate the TUFLOW model for Jimblebar creek (see Table 4-1 and Table 4-2). It was assumed that the recorded flow rates shown in Table 4-1 were applied constantly until the next recorded timestamp. Likewise, the flow volumes provided in Table 4-2 were assumed to represent the flow volume recorded since the previous timestamp.

Table 4-1: Measured flow rate at sample point (ID FNJV0150) during the discharge trial

Timestamp	Flow Rate (L/s)
15/09/2022 12:00:00 AM	0
20/11/2022 12:00:00 AM	0
17/12/2022 12:00:00 AM	200.8
24/12/2022 12:00:00 AM	200
08/01/2023 12:00:00 AM	201
13/01/2023 12:00:00 AM	192.5
20/01/2023 12:00:00 AM	162.5
28/01/2023 12:00:00 AM	140.5
05/02/2023 12:00:00 AM	115
19/02/2023 12:00:00 AM	221

Table 4-2: Measured flow volume at sample point (ID FNJV0150) during the discharge trial

Timestamp	Volume (kL)
15/09/2022 12:00:00 AM	0
14/10/2022 12:00:00 AM	0
20/11/2022 12:00:00 AM	0
17/12/2022 12:00:00 AM	140,822
24/12/2022 12:00:00 AM	116,934
08/01/2023 12:00:00 AM	256,439
13/01/2023 12:00:00 AM	87,843
20/01/2023 12:00:00 AM	117,950
28/01/2023 12:00:00 AM	107,173

Timestamp	Volume (kL)
05/02/2023 12:00:00 AM	76,507
11/02/2023 12:00:00 AM	62,409
19/02/2023 12:00:00 AM	119,287

The above flow and volume data was used to calculate discharge rates over the course of the discharge trial period for application in the TUFLOW model. The derived values are showed in Table 4-3.

Table 4-3: Derived discharge rates associated with the Jimblebar Creek discharge trial

Start Day	Discharge day	Derived discharge rate (ML/d)	Derived discharge rate (m^3/s)
09/12/2022	1	18.47	0.2138
17/12/2022	9	16.70	0.1933
24/12/2022	16	17.1	0.1979
08/01/2023	31	17.57	0.2033
13/01/2023	36	16.85	0.1950
20/01/2023	43	13.40	0.1551
28/01/2023	51	9.56	0.1107
05/02/2023	59	10.40	0.1204
11/02/2023	65	14.91	0.1726
19/02/2023	73	19.09	0.2210

For the purposes of incorporating the trial flow data into the TUFLOW model it was assumed that the discharge rate was constant between the timestamps shown in Table 4-3.

BHP also provided a dataset which contained the recorded wetting front over time associated with the discharge trial (see Table 4-4 and Figure 4-1).

Table 4-4: Recorded wetting front associated with BHP discharge trial (coordinates shown in Eastern Pilbara Grid [EPG])

LABEL	Date	X (EPG)	Y (EPG)	Days since discharge start
20221220_0900	20/12/2022	59922.20	222248	12
20221223_1250	23/12/2022	60404.37	222880.8	15
20221226_1220	26/12/2022	60805.57	223269.0	18
20221229_1015	29/12/2022	60834.18	223513.7	21
20221231_0915	31/12/2022	60890.70	223627.6	23
20230102_1000	2/01/2023	60924.00	223761.3	25
20230105_1520	5/01/2023	60941.95	223834.2	28
20230108_0730	8/01/2023	61047.34	224109.6	31
20230110_0930	10/01/2023	61047.50	224110.7	33
20230113_0945	13/01/2023	61051.94	224165.9	36
20230117_1600	17/01/2023	61052.56	224164.2	40
20230121_1200	21/01/2023	61163.74	224689.0	44
20230123_0715	23/01/2023	61163.74	224689.0	46
20230126_1415	26/01/2023	61044.73	224126.6	49
20230129_1125	29/01/2023	61044.73	224126.6	52
20230201_0900	1/02/2023	61055.18	224188.6	55
20230204_0950	4/02/2023	60723.19	223167.6	58
20230207_0730	7/02/2023	60723.31	223170.9	61
20230210_0930	10/02/2023	60716.37	223158.3	64
20230216_1400	16/02/2023	60842.20	223523.0	70
20230220_0900	20/02/2023	61037.61	224057.2	74

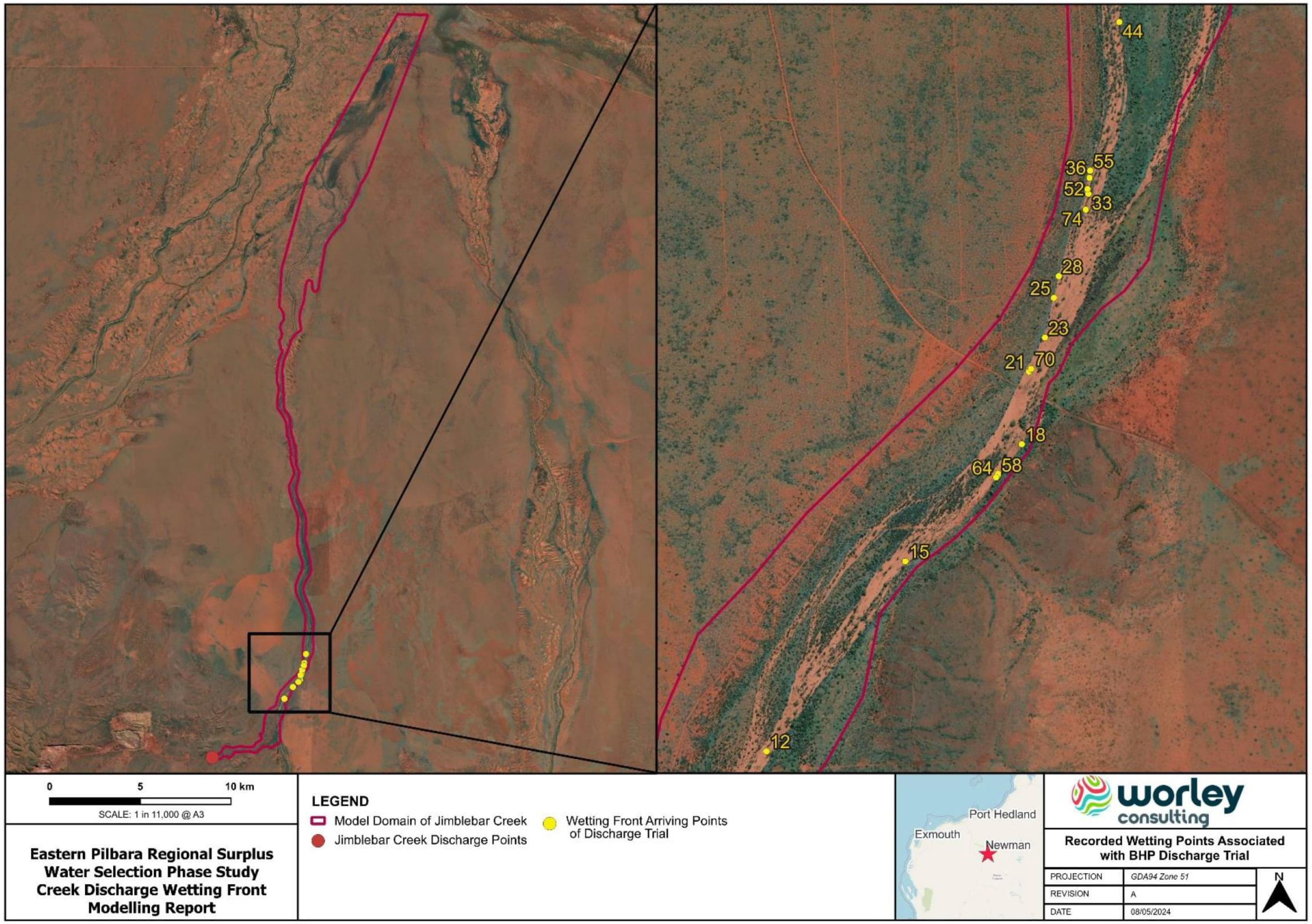

Figure 4-1: Recorded wetting front points associated with BHP discharge trial (numbers represent days since commencement of trial)

The approach taken to calibrate the TUFLOW model to the discharge trial was an iterative one which involved adjusting the vertical and horizontal infiltration rates, suction, initial moisture, and porosity for the interflow layers to attempt to replicate the observed wetting front behaviour. These parameters were adjusted based on the expected material types within the ranges outlined in Section 3.5.

Rainfall was recorded at nearby rain gauges before and during the discharge trial, therefore a relatively high initial moisture content was adopted for all subsurface layers. The depth to clay and groundwater were not adjusted as these parameters were assigned according to the datasets outlined in Sections 3.5.2 and 3.6.

The interflow functionality in TUFLOW calls for each of the layers to be assigned a certain soil type. The soil types and their associated parameters that were used in the calibration process are outlined in Table 4-5. The application of these soil types and their relative thicknesses was as per Table 4-6.

- Soil type 1 represents the alluvium in the upper vadose zone and was therefore applied to the first interflow layer below the ground surface.
- The second interflow layer represents the subsurface alluvium/colluvium above the underlying clay/bedrock. This interflow layer was represented by soil type 2, 3 or 4.
- The lowest interflow layer was set to soil type 5.

A visual representation of the interflow layer schematisation is presented in Figure 4-2.

The calibration focused on the variation of the soil type adopted for the middle interflow layer and the extent over which that soil type applied. This was largely to do with the fact that the TUFLOW model consistently predicted that the wetting front progressed slower than what was recorded during the discharge trial.

The uppermost layer required its parameters be set to the minimum k_v and k_h values and maximum initial moisture content in order to speed up the propagation of the wetting front as much as possible to match the discharge trial data points. Increases in k_v and k_h for the second interflow layer were then applied to slow the wetting front in the TUFLOW model, as required.

The extents of the different soil types for the second interflow layer were set based on information from surface geological mapping as well as the iterative calibration process which aimed to match the modelled wetting front with the recorded trial data. Figure 4-3 shows the top of clay surface adopted in the model (i.e., the base of the second interflow layer), as well as the extents over which the different soil types for the second interflow layer applied.

Table 4-5: Interflow layer parameterisation

Soil type & number	k_v (mm/hr)	k_h (mm/h)	Suction (mm)	Porosity	Initial moisture
Alluvium 1	12.5	125	200	0.1	0.099
Alluvium/Colluvium 2	12.5	125	-	0.1	0.099
Alluvium/Colluvium 3	41.6	416	-	0.25	0.249
Alluvium/Colluvium 4	27.08	270.8	-	0.175	0.07
Clay/Bedrock 5	0.08	0.042	-	0.02	0.019

Table 4-6: Interflow layer thickness

Soil layer (number)	Thickness (m)	Soil type
1 (1)	0.5	1
2 (2, 3 or 4)	Varied, set by the modified regolith surface (ranged between 6-30 m)	2, 3 or 4
3 (5)	1	5

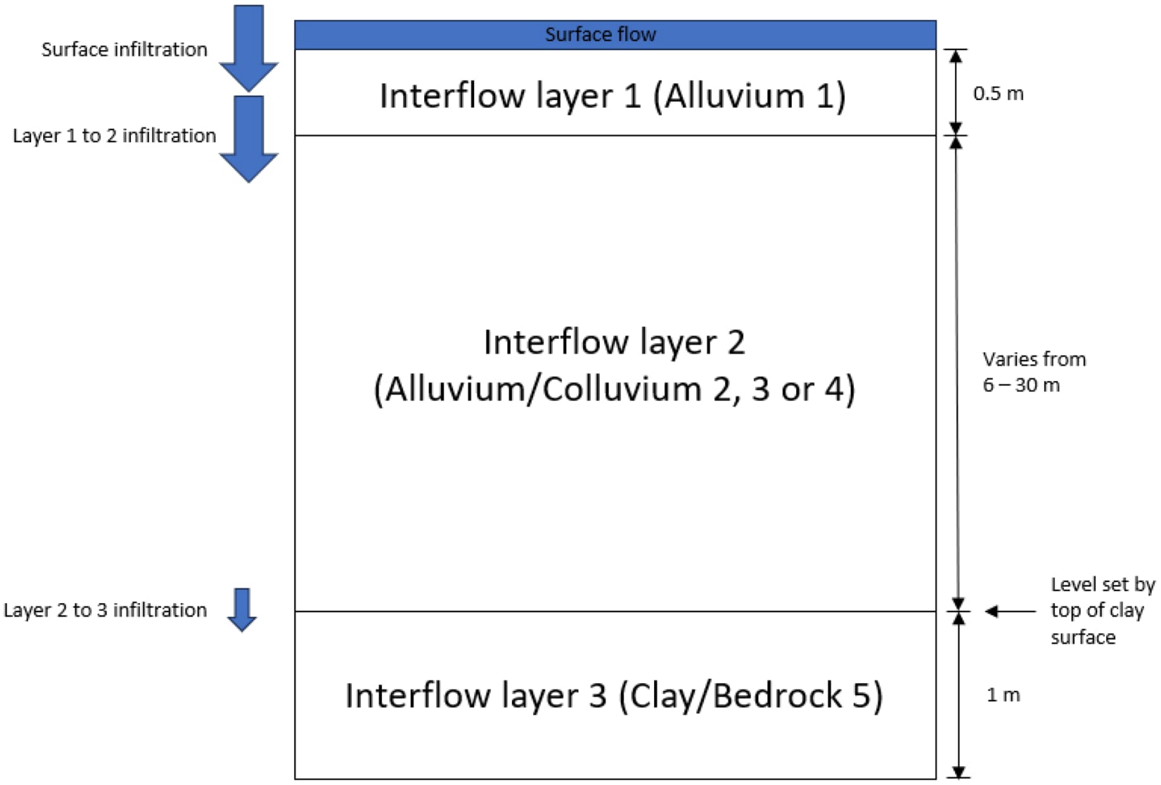

Figure 4-2: Cross-sectional schematisation of interflow layers in TUFLOW model

Table 4-7 presents the outcome of the calibration for each day that the wetting front location was measured. Table 4-8 outlines the timing lag between the TUFLOW model and the discharge trial.

The results indicate that the wetting front in the TUFLOW model progressed considerably slower than the measured discharge trial. This is likely due to the evapotranspiration losses adopted in the model being higher than reality during the discharge trial period. This was evident in the analysis of the model results as after the discharge was ceased on day 74, the wetting front began to recede. The modelled wetting front only reached the same distance as the discharge trial did on day 33, however, with a lag time of 54 days.

Table 4-7: Wetting front distance between the model results and the observed trial data.

Trial Day	Distance between TUFLOW wetting front and trial data (m)
12	-1540
15	-1950
18	-1820
21	-1670
23	-1630
25	-1800
28	-1360
31	-1370
33	-1320
36	-1390
40	-1000
44	-1580
46	-1580
49	-1010
52	-1000
55	-1080
58	0
61	0
64	170
70	-34
74	-470

Table 4-8: Timing lag between trial and TUFLOW wetting front reaching the same point

Trial Day	Model day at same point as trial	Lag days
12	22	10
15	30	15
18	62	44
21	71	50
23	74	51
25	79	54
28	80	52

Trial Day	Model day at same point as trial	Lag days
31	87	56
33	87	54
36	-	-
40	-	-
44	-	-
46	-	-
49	-	-
52	-	-
55	-	-
58	-	-
61	-	-
64	-	-
70	-	-
74	-	-

The developed wetting front model showed an improving match with the observed wetting front distance over time. However, it must be noted that the model wetting front was consistently behind the observed wetting front with regards to timing. Potential reasons for this difference could be as follows:

- The value of 8.5 mm/day for evaporation is based on the annual average pan evaporation in the region. Given that the discharge trial occurred during the wet season, it could be the case that the increased atmospheric humidity may have resulted in lower evaporation losses. The evaporation rate adopted in the model may have slowed wetting front predicted by the TUFLOW by too much. Future project phases should consider including seasonal variation in evapotranspiration losses to improve model accuracy.

- Variations in the soil type and thickness which control the storage capacity could not be adequately estimated in the model due to a relative lack of supporting drilling data. The presence of low permeability subsurface layers, where present, would have sped the propagation of the wetting front. The TUFLOW model assumed there was no such layers.

- Uncertainty regarding the adopted groundwater surface elevation dataset, which only covered a small portion of Jimblebar upstream. The groundwater elevation from the available borehole data had to be extrapolated and applied to areas without available borehole data. How this groundwater surface compared to the actual groundwater levels at the time of the discharge trial is unknown.

5 PREDICTIVE MODELLING

5.1 Discharge scenarios

[redacted]

A summary of the relevant surface geological units applicable to each modelled discharge point in provided in Table 5-1:

Table 5-1: Surface geological units for discharge points

Discharge Points	Surface Geological Units
Thirteen Creek	Q_a - Alluvium
01_Thirteen	
02_Thirteen_unnamed	
03_Thirteen_unnamed	
01_Car_East	Q_w - Colluvium and alluvium
02_Car_East	Q_s - Aeolian sand
03_Car_East	Q_w - Colluvium and alluvium

Table 5-2 presents the respective parameter ranges for the relevant surface geological units based on RPS (2015). A value in the middle of the proposed range for interflow layer parameters (see Table 5-2 to Table 5-5) was selected for predictive simulations. The application of these soil types and their relative thicknesses was as per Table 5-6.

Table 5-2: Surface geological units and suggested parameter ranges (RPS, 2015)

Unit	Symbol	K_v (mm/h)	K_h (mm/h)	Porosity	Suction (mm)
Alluvium	Q_a	12-42	3-10	0.1-0.25	200
Colluvium & alluvium	Q_w	8-42	2-10	0.1-0.2	200
Eolian sand	Q_s	8-17	2-4	0.1-0.25	200

Table 5-3: Interflow layer parameterisation for Thirteen Creek (including test pump discharge from 01_Thirteen, 02_Thirteen_unnamed and 03_Thirteen_unnamed)

Soil type & interflow layer number	k_v (mm/hr)	k_h (mm/h)	Suction (mm)	Porosity	Initial moisture
Alluvium 1	27	271	200	0.1	0.099
Alluvium/Colluvium 2	27	271	-	0.175	0.07
Clay/Bedrock 3	0.08	0.04	-	0.02	0.019

Table 5-4: Interflow layer parameterisation for Caramulla test pumping discharge points (01_Car_East, 03_Car_East)

Soil type & interflow layer number	k_v (mm/hr)	k_h (mm/h)	Suction (mm)	Porosity	Initial moisture
Alluvium 1	27	271	200	0.1	0.099
Alluvium/Colluvium 2	25	250	-	0.15	0.07
Clay/Bedrock 3	0.08	0.042	-	0.02	0.019

Table 5-5: Interflow layer parameterisation for Caramulla test pumping discharge point (02_Car_East)

Soil type & interflow layer number	k_v (mm/hr)	k_h (mm/h)	Suction (mm)	Porosity	Initial moisture
Alluvium 1	27	271	200	0.1	0.099
Eolian sand 2	12.5	125	-	0.175	0.07
Clay/Bedrock 3	0.08	0.042	-	0.02	0.019

Table 5-6: Interflow layer thickness

Interflow layer	Thickness (m)	Soil type
1 (Top)	0.5	1
2 (Middle)	Varied, set by the modified regolith surface (ranged between 6-30 m)	2
3 (Bottom)	1	3

The respective discharge locations are depicted in Figure 5-1, and the modelled scenarios are outlined in Table 5-7. All model scenarios involved output of results on a daily basis.

Table 5-7: Discharge modelling scenarios

Model creek system	Discharge location	Discharge rate(s)	Model run time (hours)
[redacted]	[redacted]	[redacted]	[redacted]
		[redacted]	[redacted]
		[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]
Test Pumping Discharge (Caramulla Creek & Thirteen Creek)	01_Thirteen	Continuous 7.7 ML/d	3,600
	02_Thirteen_unnamed		
	03_Thirteen_unnamed		
	01_Car_East		
	02_Car_East		
	03_Car_East		

The flow distances associated with each discharge scenario are shown in Table 5-8. Plots of wetting front distance vs time are presented in Figure 5-2 and Figure 5-3. Maps showing the flow path and final model output for each of the scenarios are presented in Figure 5-4 to Figure 5-9.

Table 5-8: Estimated flow distances associated with each discharge scenario.

Creek system	Discharge location	Discharge scenario	Day	Wetting Front Distance (km)
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
			[redacted]	[redacted]
			[redacted]	[redacted]
			[redacted]	[redacted]
			[redacted]	[redacted]
			[redacted]	[redacted]
			[redacted]	[redacted]
			[redacted]	[redacted]
			[redacted]	[redacted]
			[redacted]	[redacted]
			[redacted]	[redacted]
		[redacted]	[redacted]	[redacted]
			[redacted]	[redacted]
			[redacted]	[redacted]
			[redacted]	[redacted]
			[redacted]	[redacted]
			[redacted]	[redacted]
			[redacted]	[redacted]
			[redacted]	[redacted]
			[redacted]	[redacted]
			[redacted]	[redacted]
			[redacted]	[redacted]
		[redacted]	[redacted]	[redacted]
			[redacted]	[redacted]
			[redacted]	[redacted]
			[redacted]	[redacted]
			[redacted]	[redacted]
			[redacted]	[redacted]
			[redacted]	[redacted]
			[redacted]	[redacted]
			[redacted]	[redacted]
			[redacted]	[redacted]
			[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
			[redacted]	[redacted]
			[redacted]	[redacted]
			[redacted]	[redacted]
			[redacted]	[redacted]
			[redacted]	[redacted]
			[redacted]	[redacted]
			[redacted]	[redacted]
			[redacted]	[redacted]

Creek system	Discharge location	Discharge scenario	Day	Wetting Front Distance (km)
			[redacted]	[redacted]
			[redacted]	[redacted]
Test pump discharge	01_Thirteen	Continuous 7.7 ML/d for 150 days	30	1.1
			60	2.1
			90	2.8
			120	3.3
			150	3.7
	02_Thirteen_unnamed	Continuous 7.7 ML/d for 150 days	30	1.3
			60	1.7
			90	1.9
			120	2.3
			150	2.5
	03_Thirteen_unnamed	Continuous 7.7 ML/d for 150 days	30	0.4
			60	0.5
			90	0.7
			120	0.8
			150	0.9
	01_Car_East	Continuous 7.7 ML/d for 150 days	30	0.3
			60	0.3
			90	0.5
			120	0.5
			150	0.6
	02_Car_East	Continuous 7.7 ML/d for 150 days	30	0.4
			60	0.6
			90	0.8
			120	1.0
			150	1.1
	03_Car_East	Continuous 7.7 ML/d for 150 days	30	0.5
			60	0.8
			90	1.0
			120	1.1
			150	1.2

[redacted]

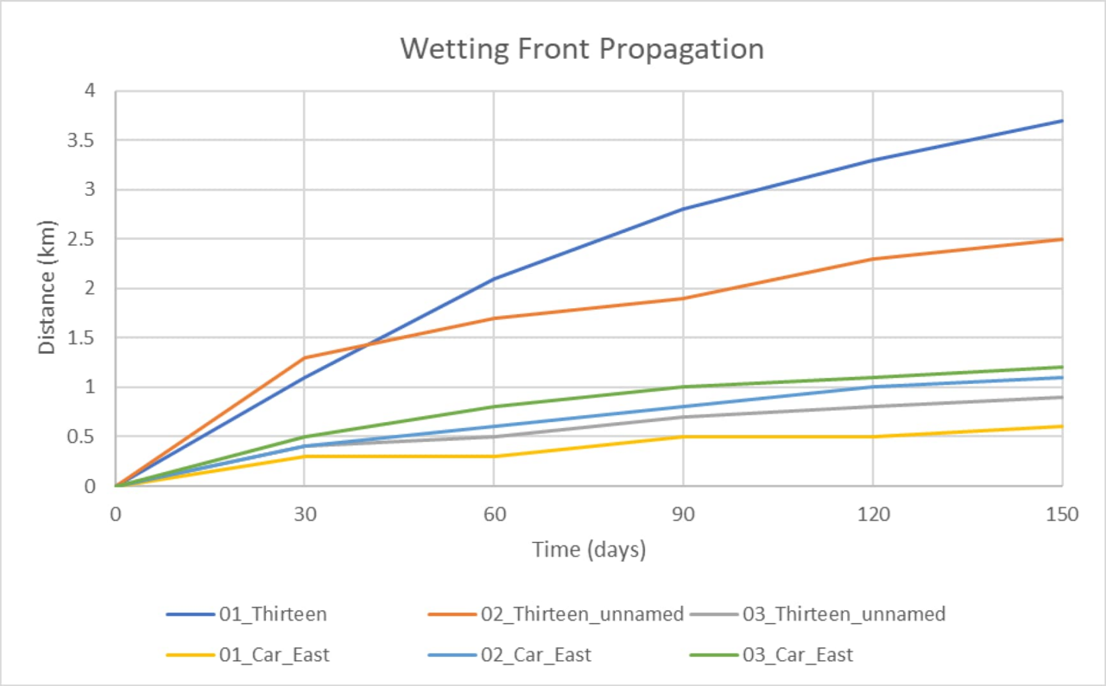

Figure 5-3: Wetting front propagation for proposed test pump locations (all 7.7 ML/d)

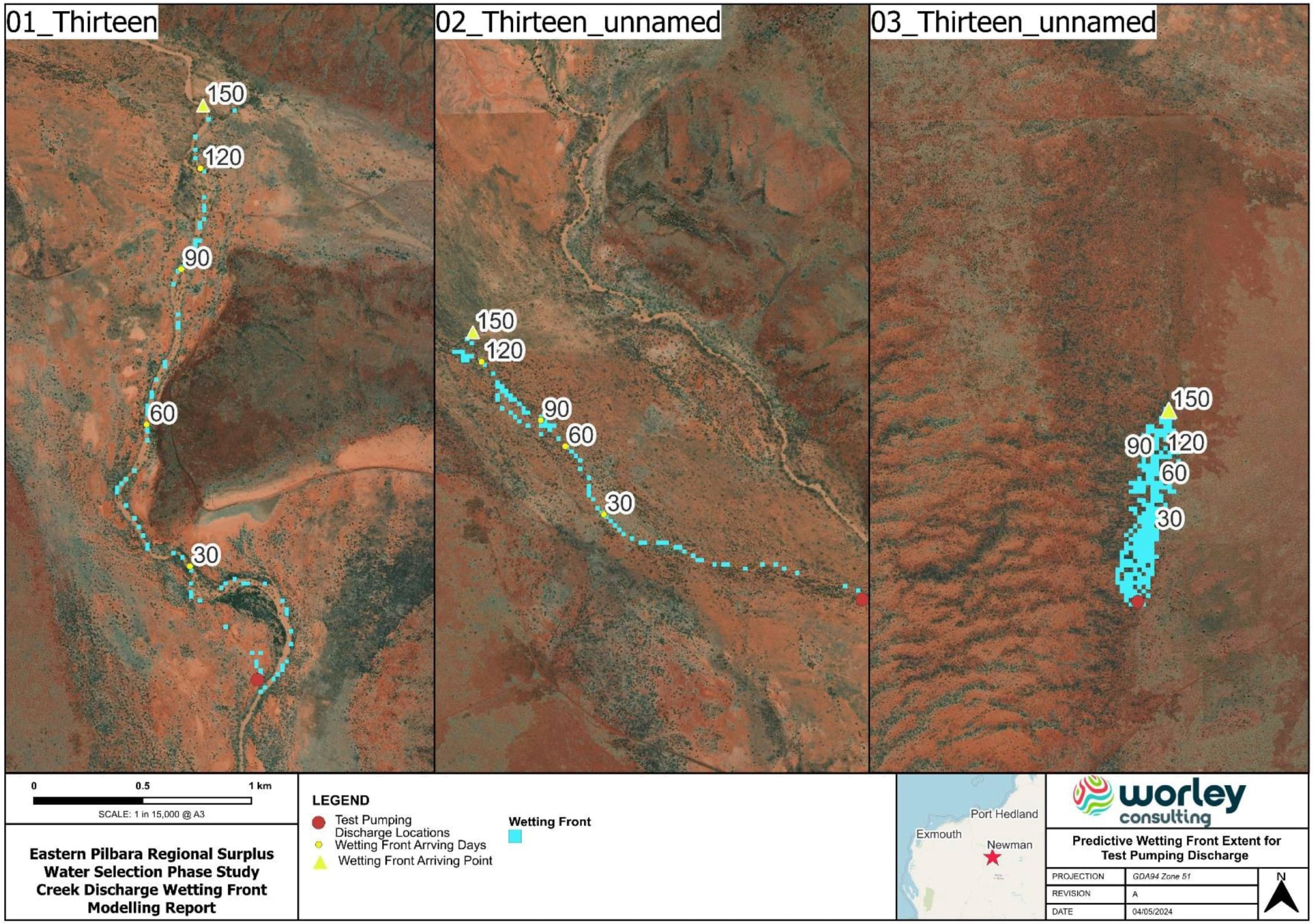

Figure 5-8: Estimated wetting front associated with proposed test pumping discharge on Thirteen Creek

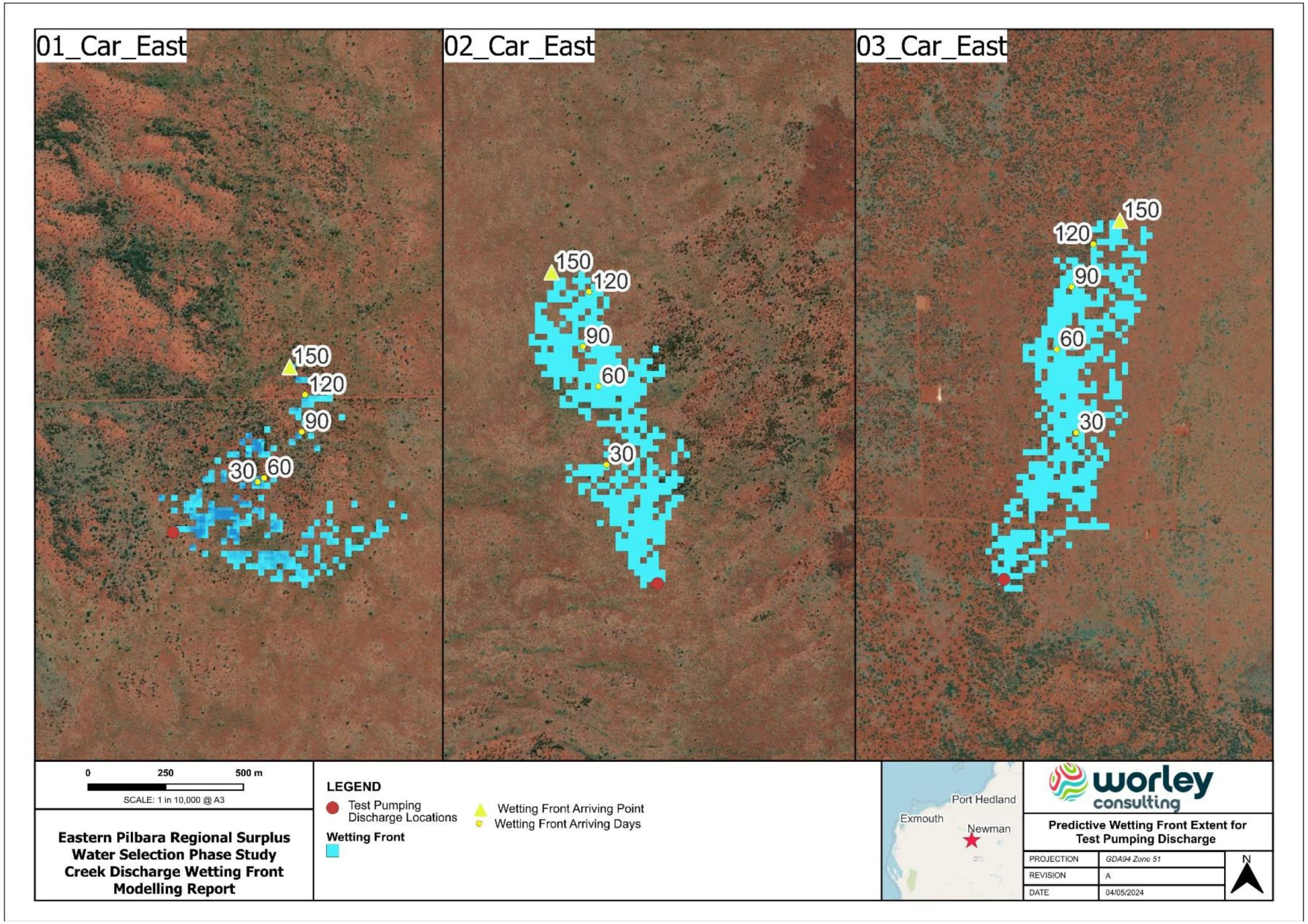

Figure 5-9: Estimated wetting front for proposed test pumping discharge on Caramulla Creek

7 CONCLUSION

[redacted]th [redacted]The estimated flow distances associated with each discharge scenario are shown in Table 7-1.

Table 7-1: Modelled wetting front distances associated with each discharge scenario

	Discharge location	Discharge scenario	Day	Wetting Front Distance (km)
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
			[redacted]	[redacted]
			[redacted]	[redacted]
			[redacted]	[redacted]
			[redacted]	[redacted]
			[redacted]	[redacted]
			[redacted]	[redacted]
			[redacted]	[redacted]
			[redacted]	[redacted]
			[redacted]	[redacted]
			[redacted]	[redacted]
		[redacted]	[redacted]	[redacted]
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			[redacted]	[redacted]
			[redacted]	[redacted]
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			[redacted]	[redacted]
			[redacted]	[redacted]
			[redacted]	[redacted]
			[redacted]	[redacted]
			[redacted]	[redacted]
		[redacted]	[redacted]	[redacted]
			[redacted]	[redacted]
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			[redacted]	[redacted]
			[redacted]	[redacted]
			[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
			[redacted]	[redacted]
			[redacted]	[redacted]
			[redacted]	[redacted]
			[redacted]	[redacted]
			[redacted]	[redacted]
			[redacted]	[redacted]

	Discharge location	Discharge scenario	Day	Wetting Front Distance (km)
			[redacted]	[redacted]
			[redacted]	[redacted]
			[redacted]	[redacted]
			[redacted]	[redacted]
Test pump discharge	01_Thirteen	Continuous 7.7 ML/d for 150 days	30	1.1
			60	2.1
			90	2.8
			120	3.3
			150	3.7
	02_Thirteen_unnamed	Continuous 7.7 ML/d for 150 days	30	1.3
			60	1.7
			90	1.9
			120	2.3
			150	2.5
	03_Thirteen_unnamed	Continuous 7.7 ML/d for 150 days	30	0.4
			60	0.5
			90	0.7
			120	0.8
			150	0.9
	01_Car_East	Continuous 7.7 ML/d for 150 days	30	0.3
			60	0.3
			90	0.5
			120	0.5
			150	0.6
	02_Car_East	Continuous 7.7 ML/d for 150 days	30	0.4
			60	0.6
			90	0.8
			120	1.0
			150	1.1
	03_Car_East	Continuous 7.7 ML/d for 150 days	30	0.5
			60	0.8
			90	1.0
			120	1.1
			150	1.2

The net recharge to groundwater estimated based on water balance method and recorded streamflow data, suggests the net creek infiltration rate of 0.36 m/year for the studied area.

8 LIMITATIONS

The inclusion of the interflow feature to facilitate horizontal flow within cumulative infiltration layers beneath the DEM surface within the TUFLOW model is an improvement on previous versions of TUFLOW which treated infiltration as a one-way process. However, as stated in the TUFLOW 2023-02 release notes, it is not intended to replace detailed groundwater modelling. Given the complexity associated with groundwater flow, assumptions will invariably be required to model it. With assumptions come limitations and uncertainty.

The approach taken in this study involved the representation of the subsurface zone as three distinct layers, with variations in hydraulic parameters to reflect different material types. In reality, a greater number of subsurface layers is expected to exist in all of the creek systems that were modelled, with an increased spatial and geometric variability in the hydraulic characteristics of each layer. For example, it is possible that there are sections of Thirteen Creek that have subsurface clay lenses which would reduce infiltration capacity in those areas.

The data available to calibrate the Jimblebar Creek model was limited to a single discharge trial. The duration of the discharge trial meant that it was not possible to take into account any form of seasonal variability with regards to variables such as depth to groundwater, initial soil moisture and evapotranspiration. As such, the calibration of the Jimblebar Creek model should be taken as a snapshot in time that may not be applicable to all times of the year or pre-wetting scenarios.

The process of evaporation and evapotranspiration in the TUFLOW model is also subject to limitations. Using negative rainfall to simulate evaporation means that this loss only occurs from cells that are wet (i.e., they have water on the surface). This is a limitation of the TUFLOW software which results in an underestimation of the evapotranspiration losses form stream banks when compared to reality. Additionally, the seasonal variation of evapotranspiration was not reflected in the TUFLOW model.

Despite the above limitations, the modelling undertaken is considered to have produced reasonable estimates that can inform BHP’s management of surplus water.

9 RECOMMENDATIONS

Recommendations for the DPS to improve the accuracy of the predicted wetting front extents include but are not limited to the following:

- [redacted]
- revise and update net groundwater recharge estimates based on available streamflow/rainfall data,
- include variations in and sensitivity analysis of evapotranspiration,
- [redacted]
- update regolith surface data based on any new borehole information that becomes available,
- investigate alternative arrangements of interflow layers to improve model calibration (e.g., simulate the existence of low permeability layers within the alluvial aquifer, or consolidate multiple interflow layers into a single subsurface layer), and
- consider comparing results of TUFLOW interflow modelling with other software (e.g., MODFLOW’s stream flow routing package, SFR2).

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