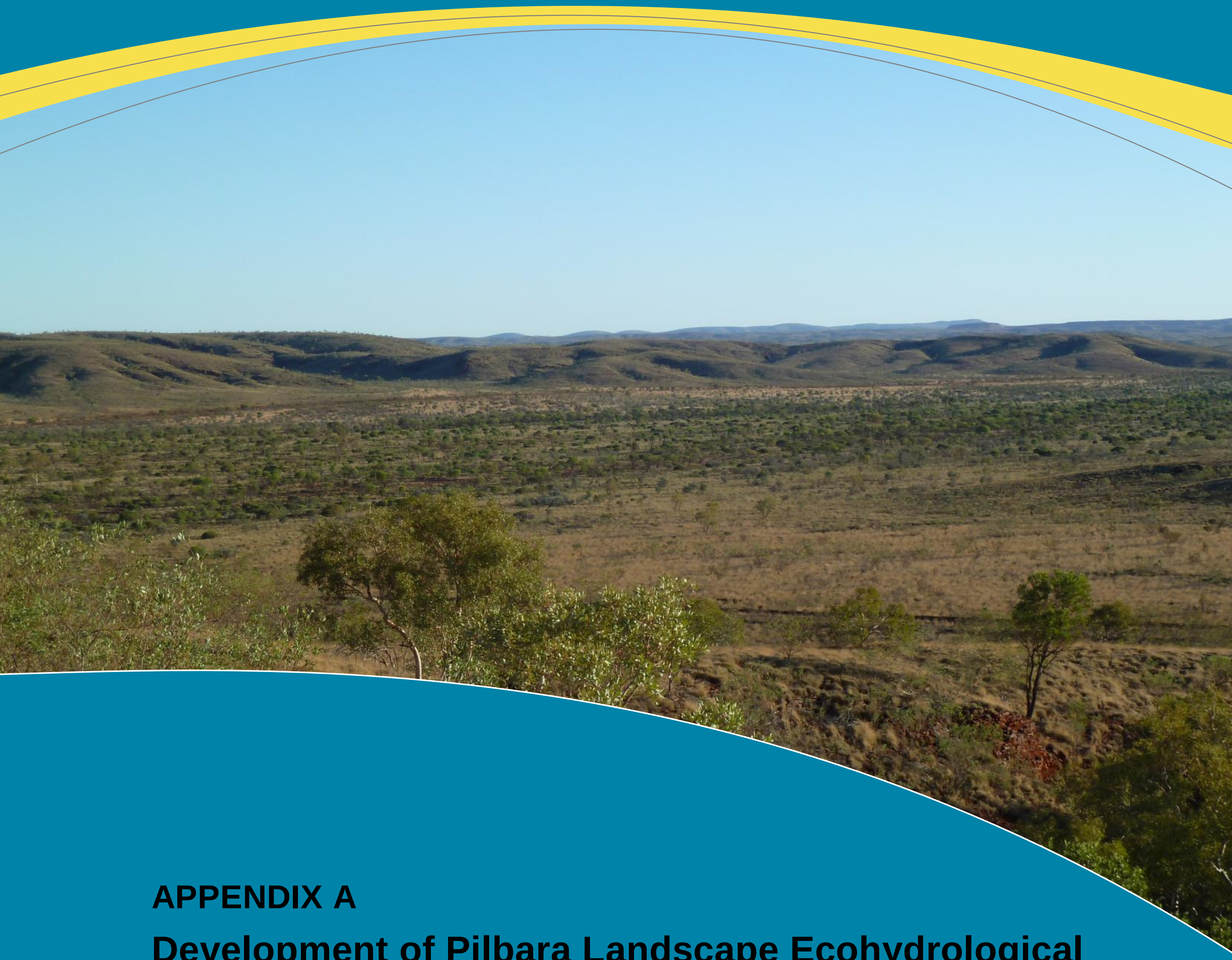

BUILDING A BETTER WORLD

APPENDIX A

Development of Pilbara Landscape Ecohydrological Units

Prepared for BHP Billiton Iron Ore

May 2015

QUALITY STATEMENT

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Executive Summary

BHP Billiton Iron Ore Pty Ltd (BHPBIO) has developed ecohydrological conceptual models (ECMs) for four project areas in the central Pilbara region: Fortescue Marsh, Marillana, Central Pilbara Hub and Eastern Pilbara Hub respectively. The ECMs integrate knowledge of hydrological and ecological systems and processes in Pilbara landscapes.

As part of the ECM development process, the landscapes of BHPBIOs project areas were partitioned into a series of ecohydrological units (EHUs) defined as 'landscape elements with broadly consistent and distinctive ecohydrological attributes'. This report describes the conceptual basis for defining the EHUs, how they are arranged and connected within regional landscapes, and how they can be spatially represented for the purposes of mapping and GIS analysis.

EHUS can be distinguished on the basis of dominant water balance processes operating within them. Although there are few quantitative studies of landscape water balance in the Pilbara, it is possible to use existing topographic, geology, geomorphology, drainage and vegetation datasets to make inferences about the relative importance of the various water balance components in landscape mosaics. On this basis a set of five broadscale ecohydrological factors were formulated for classifying EHUs in BHPBIOs project areas, as follows:

1. Landscape position and land surface types, including slope and soil characteristics;
2. Surface drainage/redistribution patterns and processes;
3. Connectivity and interactions between surface and groundwater systems;
4. Major vegetation types and their water use behaviour; and
5. Occurrence and type of wetland habitats (e.g. pools, springs, ephemeral lakes/claypans, rockholes).

These factors were used to classify nine EHUs:

- EHU 1: Upland source areas - hills, mountains, plateaux.
- EHU 2: Upland source areas – dissected slopes and plains.
- EHU 3: Upland transitional areas – drainage floors within EHUs 1 and 2 which tend to accumulate surface flows from up-gradient.
- EHU 4: Upland channel zones - channel systems of higher order streams which are typically flanked by EHU3 and dissect EHUs 1 and 2.
- EHU 5: Lowland sandplains – level to gently undulating surfaces with occasional linear dunes. Little organised drainage but some tracts receive run-on from upland units.
- EHU 6: Lowland alluvial plains – typically of low relief and featuring low energy, dissipative drainage.
- EHU 7: Lowland calcrete plains – generally bordering major drainage tracts and termini, typically with shallow soils and frequent calcrete exposures.
- EHU 8: Lowland major channel systems and associated floodplains.
- EHU 9: Lowland receiving areas - drainage termini in the form of ephemeral lakes, claypans and flats.

The defining attributes of each EHU are detailed in Table 2 of the main report, and diagrammatic ecohydrological conceptualisations are provided in Figures 3 to 9.

The spatial definition of EHUs is necessary for environmental impact assessment purposes. A procedure for spatially defining EHU polygons was developed using the following datasets:

- Pilbara land system mapping (Van Vreeswyk *et al.* 2004);
- Surface drainage networks derived using a high resolution (~5 m accuracy) digital elevation model (DEM) provided by BHPBIO;
- Depth to groundwater inferred from existing bore locations;
- Vegetation mapping (leaf area index, structure and dominant species); and
- Landsat NDVI (Normalized Difference Vegetation Index).

It should be noted that EHUS are landscape scale features, and accordingly the EHU polygons have been developed at a landscape scale resolution. Some additional minor adjustments to selected polygons were made at the BHPBIO project area level, in order to account for local area ecohydrological features requiring higher resolution delineation. These are described in Section 3.6 of the main report.

BHP Billiton Iron Ore

Development of Pilbara Landscape Ecohydrological Units

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1 Introduction

BHP Billiton Iron Ore is undertaking a Strategic Environmental Assessment (SEA) for the Pilbara Expansion, which comprises construction and operation of a number of new operational iron ore hubs, expansion of existing operational iron ore hubs, and capacity upgrades to the main Newman to Port Hedland rail line and associated spur lines to existing and proposed hubs. As part of the SEA, BHP Billiton Iron Ore has undertaken an ecohydrological change assessment related to its current operations (baseline conditions), as well as proposed operations associated with 30% development and full development change scenarios. The change assessment provides a framework for evaluating the potential effects of hydrological change resulting from the Pilbara Expansion, and also cumulative change associated with third party operations.

In support of the ecohydrological change assessment, BHP Billiton Iron Ore Pty Ltd (BHPBIO) has developed ecohydrological conceptual models (ECMs) for the four regions that collectively comprise the Pilbara Expansion study area including (Refer to Map 1 of the ecohydrological change assessment report):

- Fortescue Marsh;
- Central Pilbara;
- Eastern Pilbara; and
- Marillana Creek.

The ECMs provide a basis for understanding landscape scale ecohydrological processes, and the assessment of potential environmental impacts due to hydrological change arising from BHPBIOs mining and infrastructure development activities.

The ECMs integrate knowledge of hydrological and ecological systems and processes in the study area. As part of the ECM development process, the landscapes of the study area were partitioned into a series of ecohydrological units (EHUs) defined as 'landscape elements with broadly consistent and distinctive ecohydrological attributes'.

This report describes the conceptual basis for defining the EHUs, how they are arranged and connected within regional landscapes, and how they can be spatially represented for the purposes of mapping and GIS analysis.

2 Conceptualisation of EHUs

2.1 Overview

Water arrives in the terrestrial landscape as rainfall, and is then redistributed spatially and temporally via a complex assortment of pathways. These pathways include abiotic and biotic elements. Particularly in dryland environments such as the Pilbara, relationships exist between landscape patterns of water distribution and ecosystem components such as vegetation and aquatic ecosystems (Turnbull *et al.* 2012; Merino-Martín *et al.* 2012; Miller *et al.* 2012; Mueller *et al.* 2013).

Different parts of the landscape have different hydrological and ecological characteristics. For a given landscape element, many of these characteristics are determined by the dominant water balance processes operating within the landscape element. The major components of the water balance in Pilbara landscapes are presented in Figure 1.

Each of the water balance terms in Figure 2 is influenced by a complex assortment of factors, many of which may be interdependent. Examples are provided as follows:

- Infiltration – some of the factors affecting infiltration include rainfall intensity and duration, evaporation, topography (slope angle and length, slope shape *etc*), basement rock exposures, fissure distribution, various soil physico-chemical properties (crusting, dispersiveness, surface pavements *etc*), moisture content of the soil surface and vegetation cover/spatial configuration (Zhang *et al.* 2014; Wainwright & Bracken 2011).
- Surface drainage - some of the factors affecting surface drainage patterns include slope angle and length, slope shape (e.g. linear, convex or concave), flow path convergence, infiltration rates, terrace structures and vegetation cover/spatial configuration (Reaney *et al.* 2014; Wainwright & Bracken 2011).
- Groundwater recharge and discharge - some of the factors affecting groundwater recharge and discharge processes include topography (diffuse versus concentrated recharge), infiltration, evaporation, storage in the unsaturated regolith, preferred pathways in the unsaturated regolith, impeding layers between the land surface and the watertable, and vegetation water use (Shanfield & Cook 2014; Scanlon *et al.* 2002).

There are few studies in which the components of the water balance in different Pilbara landscapes have been directly measured or quantified. However it is possible to use existing topographic, geology, geomorphology, drainage and vegetation datasets to make inferences about the relative importance of the various water balance components in landscape mosaics. In combination these datasets provide a basis for describing ecohydrological regimes in different landscape elements, and also enable the major ecohydrological connectivities between different landscape elements to be explored.

Building on the preceding discussion of water balance concepts, and taking into account the availability of relevant Pilbara datasets, a set of five broadscale ecohydrological factors were formulated for classifying EHUs in BHPBIOs project areas. These are listed as follows and further described in Table 1:

1. Landscape position and land surface types, including slope and soil characteristics;
2. Surface drainage/redistribution patterns and processes;
3. Connectivity and interactions between surface and groundwater systems;
4. Major vegetation types and their water use behaviour; and
5. Occurrence and type of wetland habitats (e.g. pools, springs, ephemeral lakes/claypans, rockholes).

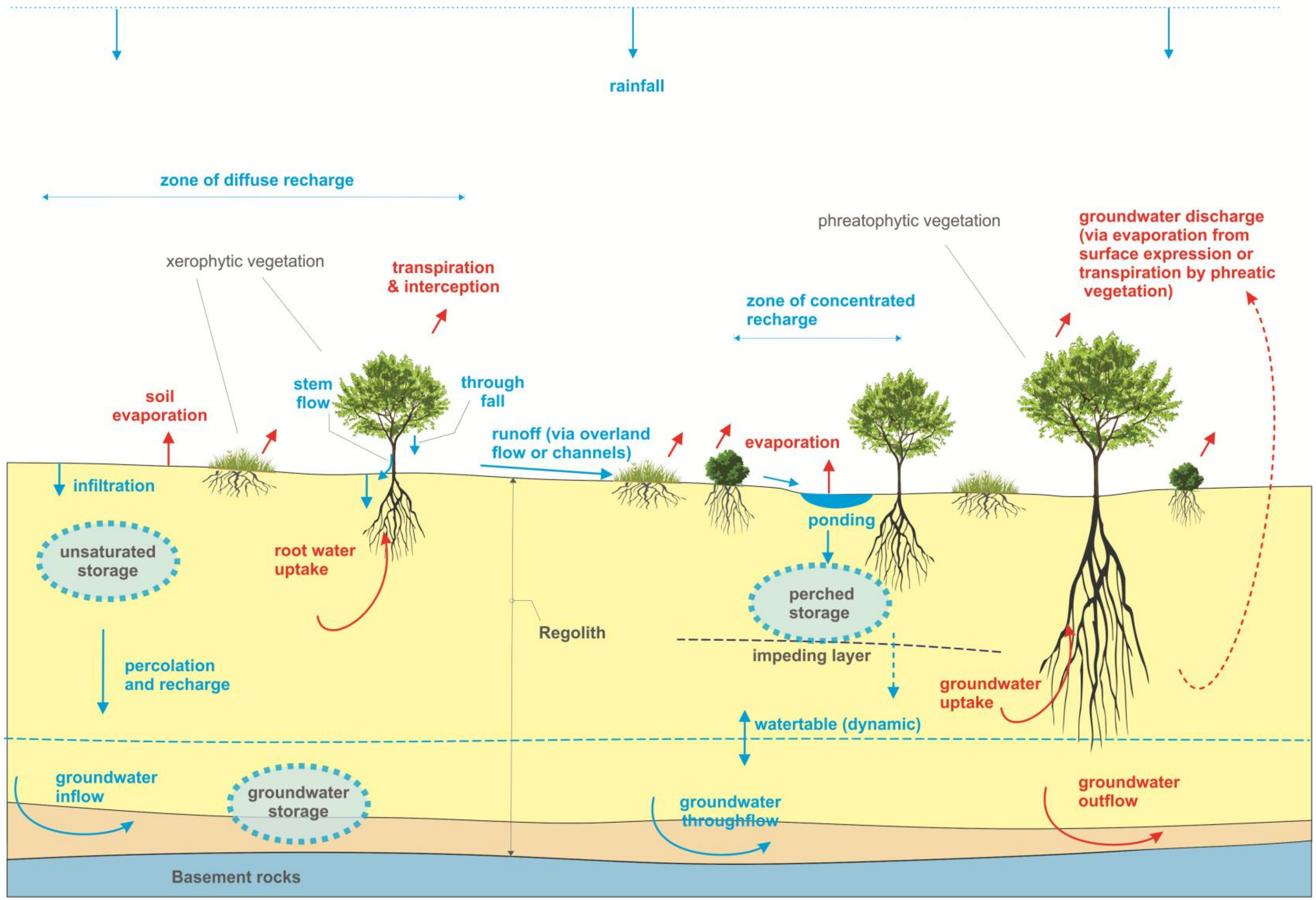


Figure 1 Major water balance components in Pilbara landscapes

Table 1 Ecohydrological factors for distinguishing different EHUs in Pilbara landscapes

Factor	Key aspects	Major landscape water balance processes
1. Landscape position and land surface types, including slope and soil profile characteristics	Uplands – low permeability surface/low storage capacity	Rainfall ⇨ storage (limited) ⇨ runoff to downgradient EHUs
	Uplands – low permeability surface/high storage capacity	
	Uplands – permeable surface/ low storage capacity	
	Uplands – permeable surface/ high storage capacity	Infiltration ⇨ storage ⇨ evapotranspiration; groundwater recharge
	Lowlands – low permeability surface/low storage capacity	Rainfall ⇨ storage (limited) ⇨ local scale redistribution to local area sinks ⇨ evapotranspiration; groundwater recharge
	Lowlands – low permeability surface/high storage capacity	
	Lowlands – permeable surface/ low storage capacity	
	Lowlands – permeable surface/ high storage capacity	Rainfall and run-on ⇨ storage ⇨ evapotranspiration; groundwater recharge
2. Surface drainage/redistribution patterns and processes	Source areas	Rainfall ⇨ storage (limited) ⇨ outflows to downgradient EHUs
	Transitional areas	Surface inflows ⇨ flow losses (evaporation; infiltration; storage; plant water use; percolation to groundwater) ⇨ outflows to downgradient EHUs
	Areas with pronounced internal (localised) water redistribution (e.g. banded vegetation formations)	Rainfall ⇨ local scale redistribution ⇨ storage ⇨ evapotranspiration; groundwater recharge
	Receiving areas	Surface inflows ⇨ storage (surface and/or subsurface) ⇨ losses (evaporation; infiltration; plant water use; groundwater recharge and discharge)

Factor	Key aspects	Major landscape water balance processes
3. Connectivity and interactions between surface and groundwater systems	Diffuse recharge zones	Rainfall ⇨ infiltration ⇨ percolation to watertable
	Concentrated recharge zones	Rainfall and run-on ⇨ infiltration ⇨ percolation to watertable
	Discharge zones	Groundwater inflow ⇨ surface expression ⇨ evaporation Groundwater inflow ⇨ phreatophytic vegetation water use ⇨ transpiration
	Aquifer connectivity	Groundwater transfer between landscape elements is a function of aquifer connectivity, hydraulic gradients and aquifer transmissivities.
4. Major vegetation types and their water use strategies	Xerophytic vegetation (principally rain fed)	Rainfall ⇨ storage (limited) ⇨ evapotranspiration
	Xerophytic vegetation (principally fed by inflows and storage)	Rainfall and run-on ⇨ storage ⇨ evapotranspiration
	Phreatophytic vegetation	Groundwater inflow ⇨ phreatophytic ic vegetation water use ⇨ transpiration The relative contribution of surface water inputs and groundwater inputs to vegetation water use may vary spatially and through time.
5. Occurrence and type of aquatic habitats (e.g. pools, springs, ephemeral lakes)	No wetlands	N/A
	Wetlands fed by surface inputs only	Rainfall and run-on ⇨ storage (surface and/or subsurface) ⇨ evapotranspiration; groundwater recharge Various wetland types such as ephemeral to persistent pools, claypans and rockholes. The contribution of surface water inputs to wetlands (i.e. flooding regimes) may vary spatially and through time.
	Wetlands fed by groundwater inputs	Groundwater inflow ⇨ surface expression ⇨ evaporation Groundwater inflow ⇨ phreatic vegetation water use ⇨ transpiration Wetland types include springs, seeps and persistent to permanent pools. The relative contribution of surface water inputs and groundwater inputs to wetlands may vary spatially and through time.

2.2 Classification of EHUs

Through consideration of the factors described Table 1, a total of nine EHUs were recognised in the landscapes of the study area. These are summarised as follows:

- EHU 1: Upland source areas - hills, mountains, plateaux.
- EHU 2: Upland source areas – dissected slopes and plains.
- EHU 3: Upland transitional areas – drainage floors within EHUs 1 and 2 which tend to accumulate surface flows from up-gradient.
- EHU 4: Upland channel zones - channel systems of higher order streams which are typically flanked by EHU3 and dissect EHUs 1 and 2.
- EHU 5: Lowland sandplains – level to gently undulating surfaces with occasional linear dunes. Little organised drainage but some tracts receive run-on from upland units.
- EHU 6: Lowland alluvial plains – typically of low relief and featuring low energy, dissipative drainage.
- EHU 7: Lowland calcrete plains – generally bordering major drainage tracts and termini, typically with shallow soils and frequent calcrete exposures.
- EHU 8: Lowland major channel systems and associated floodplains.
- EHU 9: Lowland receiving areas - drainage termini in the form of ephemeral lakes, claypans and flats.

The basis for classifying these EHUs is articulated in Table 2. Note that EHU 1 and EHU 2 have similar ecohydrological regimes, and are separated chiefly on the basis of topographic position and drainage patterns. EHUs 3 and 4 are transitional units that receive inflows from EHUs 1 and 2, and transmit flows into lowland units further downgradient.

Three types of lowland plains are recognised (EHUs 5, 6 and 7), all of which feature low relief and dissipative drainage but different surface types and soil profiles. EHU8 includes the large river systems that receive, store and transmit large volumes of water. EHU9 includes the terminal zones of drainage systems where water is accumulated and lost to evapotranspiration and deep drainage.

Schematic conceptualisations for each of EHU, depicting key components and ecohydrological processes, are provided in Figures 3 to 9 respectively.

2.3 Landscape arrangement of EHUs

The EHUs transition from upland to lowland environments, in a spatial arrangement hierarchy as depicted in Figure 9, and conceptually illustrated in Figure 10. Upland units include surface water source areas (EHUs 1 and 2) and transitional areas (EHUs 3 and 4). Lowland units include transitional units (EHUs 5, 6 and 7) and receiving units (EHUs 8 and 9); any of which may receive surface inflows from upland units in different landscape settings.

In general terms groundwater flow reflects the surface topography, with throughflow occurring in valley systems and in association with major channel systems. Palaeochannels also provide conduits for groundwater transfer. In many cases palaeochannels are broadly aligned with present day drainage networks.

As with surface flows, groundwater tends to flow towards, accumulate in and discharge from EHUs 8 and 9. Note that both of these EHUs contain zones of concentrated groundwater recharge derived from surface inputs. Within these EHUs groundwater may be close to the surface (within 10 m) and accessible to vegetation. In other EHUs the groundwater is generally deeper and not accessible to vegetation.

Table 2 EHU classification based on ecohydrological factors

EHU	Landscape position, land surface and soils	Surface drainage/redistribution patterns and processes	Connectivity and interactions between surface and groundwater systems	Major vegetation types and their water use strategies	Occurrence and type of aquatic habitats	Dominant landscape water balance processes
1	Upland areas - hills, mountains, plateaux. Low storage capacity. Land surfaces are steep and rocky. Shallow or skeletal soils with frequent bedrock exposures.	Source areas. Generally short distance overland flow into dendritic drainage networks (1st, 2nd and 3rd order streams).	Generally diffuse recharge areas. Preferential recharge can occur on a localised scale as dictated by local scale geology/regolith. Local and regional groundwater systems are deep and not accessible to vegetation.	Xerophytic vegetation (principally rain fed). Predominantly hummock grasslands.	None	Rainfall ⇩ Infiltration ⇩ Soil evaporation ⇩ Run-off
2	Upland areas – dissected slopes and plains, downgradient from EHU1. Low storage capacity. Land surface is sloping. Shallow to moderately deep colluvial soils.	Source areas. Overland flow short distance into channel drainage systems (mainly 1st to 4th order streams) which dissect the land surface.	Generally diffuse recharge areas. Preferential recharge can occur on a localised scale as dictated by local scale geology/regolith. Local and regional groundwater systems are deep and not accessible to vegetation.	Xerophytic vegetation (principally rain fed). Predominantly hummock grasslands.	None	Rainfall ⇩ Infiltration ⇩ Soil evaporation ⇩ Run-off
3	Upland areas – drainage floors within EHUs 1 and 2 which accumulate surface flows from up-gradient. Soils of variable depth derived from alluvium. Greater storage relative to soils in EHU 1 and 2.	Transitional areas. Surface accumulation and infiltration of flood flows (overland flows and channel breakouts). Excess volumes transferred to adjacent channels (EHU4).	Concentrated recharge areas (as dictated by regolith characteristics). Local and regional groundwater systems are deep and not accessible to vegetation.	Xerophytic vegetation (principally fed by inflows and storage). Smaller drainage floors support hummock grasslands; larger drainage floors support *Eucalyptus* and *Acacia* shrublands and woodlands.	None	Inflows ⇩ Infiltration ⇩ Storage ⇩ Evapotranspiration
4	Upland areas - channel systems of higher order streams (generally ≥5th order) which dissect	Transitional areas. Channel beds and banks accept and store water during flow	Concentrated recharge areas (as dictated by regolith characteristics). Regional groundwater systems	Xerophytic vegetation (principally fed by inflows and storage). Channels are typically lined	Rock pools Ephemeral and intermittent	Inflows ⇩ Infiltration

EHU	Landscape position, land surface and soils	Surface drainage/redistribution patterns and processes	Connectivity and interactions between surface and groundwater systems	Major vegetation types and their water use strategies	Occurrence and type of aquatic habitats	Dominant landscape water balance processes
	EHU1 and EHU2. Channels are high energy flow environments, subject to bed load movement and reworking. Soils of variable depth derived from alluvium including zones of deep soils. Generally high infiltration rates.	events. Large flows are transmitted downgradient. Channels uncommonly support intermittent or persistent pools/rock holes replenished by flood flows.	are typically deep and not accessible to vegetation (with the rare exception of in-channel springs). Transient or less commonly persistent shallow groundwater systems may develop beneath channels in places, as dictated by local scale geology/regolith. In rare cases these may be connected with ephemeral and intermittent pools.	with narrow woodlands of *E. victrix*, *A. citrinoviridis* and/or other *Eucalyptus* and *Acacia* species.	pools Springs (rare)	⇩ Storage ⇩ Evapotranspiration & groundwater recharge ⇩ Channel throughflow
5	Lowland sandplains - landform characterised by level or gently undulating plains up to 10 km in extent. Deep sandy soils of aeolian origin. May have significant water storage capacity. Uncommonly features linear dunes up to about 15 m in height.	Areas with minimal internal (localised) water redistribution. Poorly organised drainage. High rainfall infiltration and recharge. Runoff is minimal and if it does occur is generally localised, with accumulation in swales or depressions. Sandplains may receive and infiltrate inflows from channels deriving from up-gradient areas.	Diffuse recharge zones. Groundwater systems are generally deep and not accessed by vegetation. This EHU may include important zones of recharge, with associated groundwater mounding. Possibility of transient or more persistent perched groundwater at localised scales, depending on regolith characteristics.	Xerophytic vegetation (principally rainfed). Vegetation includes hummock grasslands, with *Acacia* spp. and other shrubs, occasional mallee Eucalypts. Generally distinctive vegetation communities relative to other EHUs. Tracts receiving run-on include *Acacia* and *Eremophila* shrublands.	None	Rainfall ⇩ Infiltration ⇩ Storage ⇩ Evapotranspiration & groundwater recharge
6	Lowland alluvial plains – broad depositional plains of low relief. Soils typically loams, earths and shallow	Areas with internal (localised) water redistribution. Complex surface water drainage and	Generally diffuse recharge zones. Groundwater systems are generally moderately deep (>10m) to deep (>20m) and not accessed by vegetation.	Xerophytic vegetation (fed by rainfall and local scale redistribution processes, and storage). Higher leaf area index in drainage foci.	None	Rainfall ⇩ Localised surface redistribution

EHU	Landscape position, land surface and soils	Surface drainage/redistribution patterns and processes	Connectivity and interactions between surface and groundwater systems	Major vegetation types and their water use strategies	Occurrence and type of aquatic habitats	Dominant landscape water balance processes
	duplex types. Subsurface calcareous hardpans are frequently encountered.	redistribution patterns. Land surfaces are generally dissected by low energy channels of variable form and size. Some areas may be subject to infrequent flooding. Infiltration may be significant at local scales in association with drainage foci.	Recharge may be constrained by hardpans.	Areas of sheetflow can occur, which may be associated with banded vegetation formations. Vegetation includes *Acacia* shrublands; less commonly Hummock grasslands, Tussock grasslands or low shrublands of Bluebush/Saltbush.		⇩ Infiltration ⇩ Storage ⇩ Evapotranspiration
7	Lowland calcrete plains – plains of low relief generally bordering major drainage tracts and termini. Shallow soils underlain by calcrete of variable thickness, which occasionally outcrops.	Areas with internal (localised) water redistribution. Complex surface water drainage and redistribution patterns. Calcrete platforms have variable permeability. Indistinct drainage, generally characterised by numerous localised drainage termini.	Diffuse recharge zones. Depth to groundwater can vary from shallow (<5m) to deep (>20m). Groundwater systems are generally not accessed by vegetation. Preferred pathways may facilitate rapid recharge at local scales, as dictated by calcrete permeability.	Xerophytic vegetation (fed by rainfall and local scale redistribution processes, and storage). Higher leaf area index in drainage foci. Vegetation includes hummock grasslands and *Acacia* scrublands with occasional Eucalypts. Generally distinctive vegetation communities relative to other EHUs.	Groundwater systems in calcrete substrates may constitute high quality stygofauna habitat.	Rainfall ⇩ Localised surface redistribution ⇩ Infiltration ⇩ Evapotranspiration & groundwater recharge
8	Lowland major channel systems and associated floodplains - supporting large flow volumes in flood events. Channels are high energy flow	Receiving areas. Channel beds and banks accept and store water during flow events. Large flows are transmitted down-gradient.	Concentrated recharge zones; also may include shallow groundwater discharge zones. Depth to groundwater can vary from shallow (near surface) to deep (>20m). Channels are significant	Areas of phreatophytic vegetation, in addition to xerophytic vegetation (principally fed by inflows and storage). Inflows from up-gradient sources sustain *Eucalyptus*	Ephemeral, persistent and permanent pools, seeps and springs.	Inflows ⇩ Ponding ⇩ Infiltration

EHU	Landscape position, land surface and soils	Surface drainage/redistribution patterns and processes	Connectivity and interactions between surface and groundwater systems	Major vegetation types and their water use strategies	Occurrence and type of aquatic habitats	Dominant landscape water balance processes
	environments, subject to bed load movement and reworking. They may be physically altered by cyclonic floods.	Soil water in the floodplains is replenished during flooding breakouts. Channels support transient, persistent and permanent pools.	recharge zones. Transient, persistent or permanent shallow groundwater systems may develop beneath channels in places, as dictated by local scale geology/regolith. These may be connected with pools in some situations. Groundwater is generally fresh. Groundwater systems can be accessible to vegetation in some situations.	and *Acacia* forest and woodland vegetation communities or tussock grasslands. EHU8 supports most of the recognised groundwater dependant vegetation communities in the central Pilbara (with the key indicator species being *Eucalyptus camaldulensis*, *E. victrix* and *Melaleuca argentea*).		⇩ Storage, evapotranspiration & groundwater recharge ⇩ Channel throughflow ⇩ Groundwater discharge (localised)
9	Lowland areas - drainage termini in the form of ephemeral lakes, claypans and bounded flats. Deep silty and clay textured soils. Variable surface salinity (resulting from evaporites). Soils may be underlain by calcrete/ silcrete hardpans of variable depth.	Receiving areas. Drainage termini receive inflows from up-gradient EHUs. Transient to persistent ponding in EHU9 may occur as dictated by flooding regimes, with spillovers possible in large flooding events. Sediment accumulation and evaporative concentration of salts, as mediated by flushing events.	Concentrated recharge zones; also may include shallow groundwater discharge zones. Depth to groundwater can vary from shallow (near surface) to deep (>20m). Groundwater may be fresh, brackish or saline. Groundwater systems can be accessible to vegetation in some situations.	May include areas of phreatophytic vegetation, in addition to xerophytic vegetation fed by inflows and storage. EHU9 areas are generally fringed or occupied by distinctive vegetation communities (e.g. *Eucalyptus victrix* woodlands, tussock grasslands or samphire). Regularly inundated areas may be largely devoid of vegetation. The vegetation is commonly adapted to waterlogging, flooding and salinity stressors.	Ephemeral lakes and claypans. May include ephemeral, persistent and permanent pools, and seeps.	Inflows ⇩ Ponding ⇩ Infiltration ⇩ Storage ⇩ Soil evaporation ⇩ Evapotranspiration & groundwater recharge ⇩ Groundwater discharge (localised)

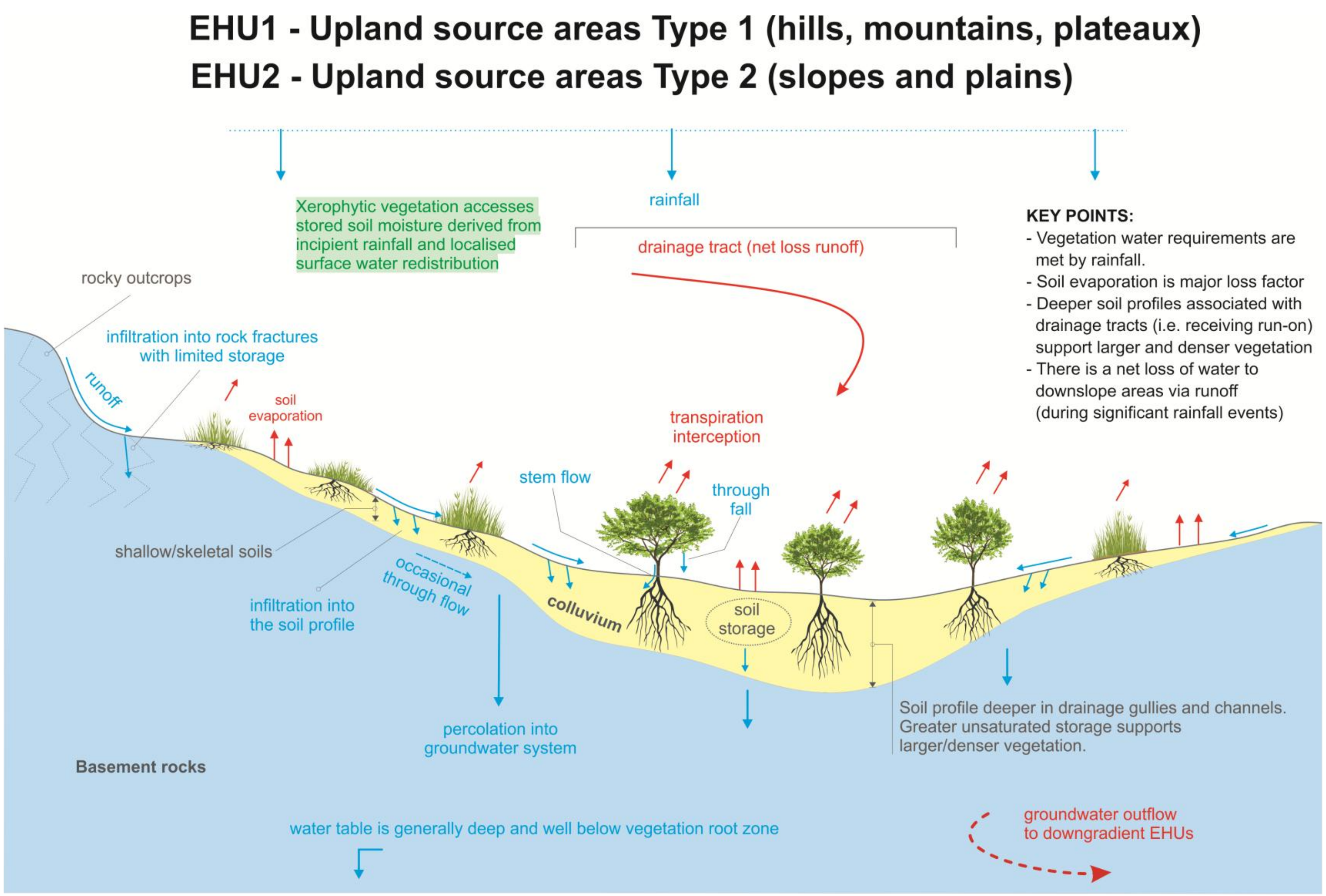


Figure 2 **EHU1 and EHU2 conceptualisation - Upland source areas**

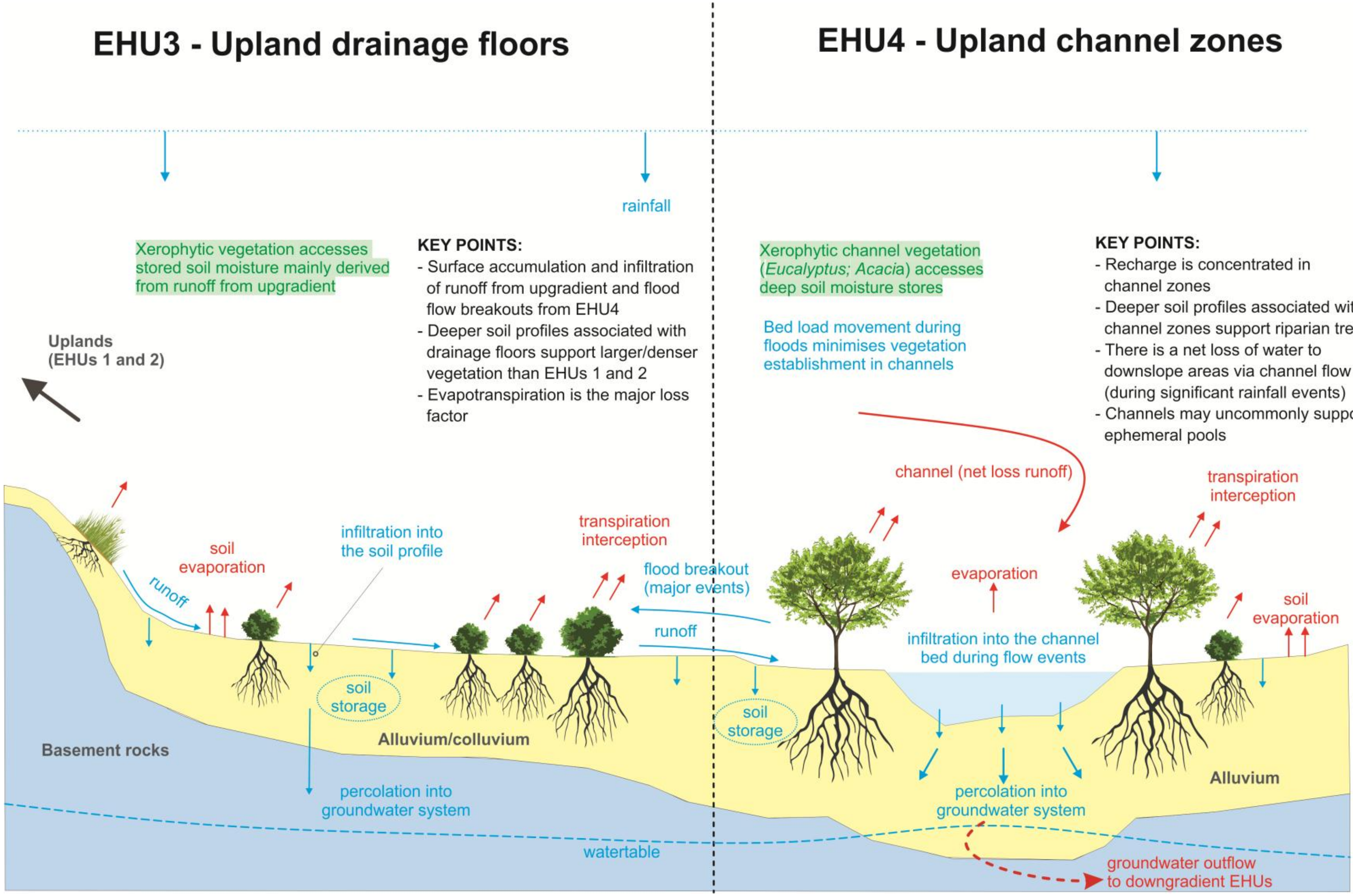


Figure 3 **EHU3 and EHU4 conceptualisation - Upland drainage floors and channel zones**

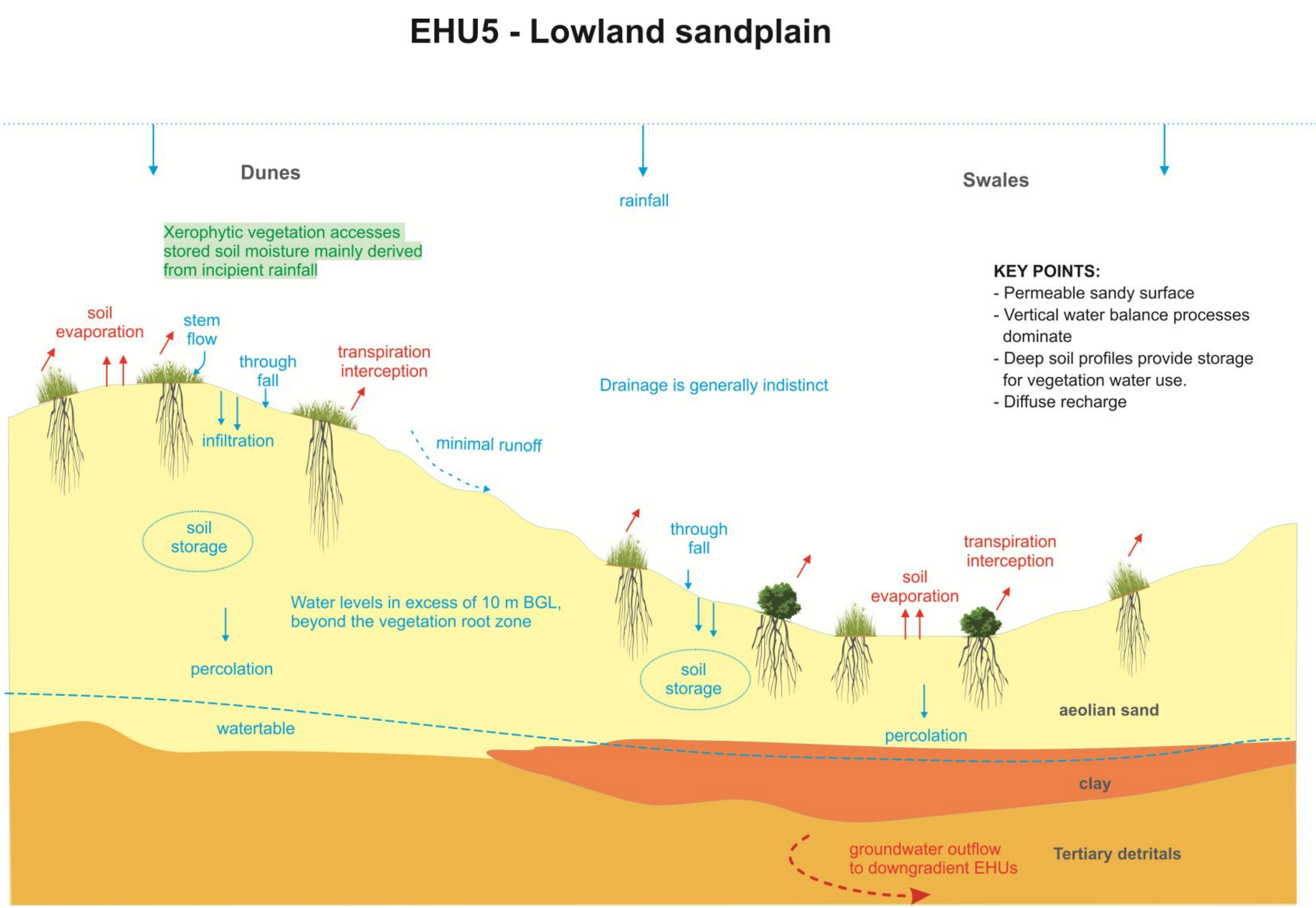


Figure 4 **EHU5 conceptualisation – Lowland sandplains**

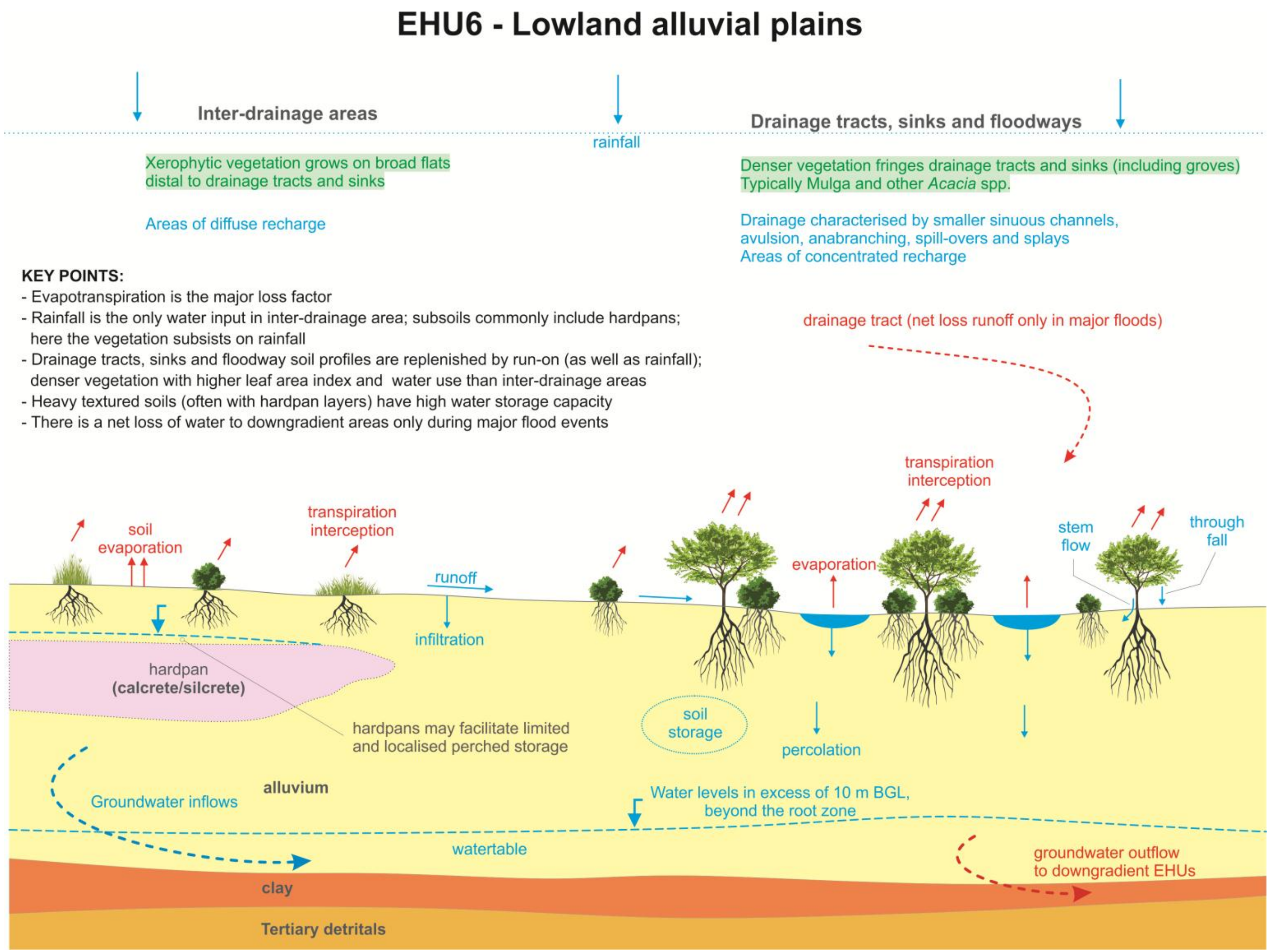


Figure 5 **EHU6 conceptualisation – Lowland alluvial plains**

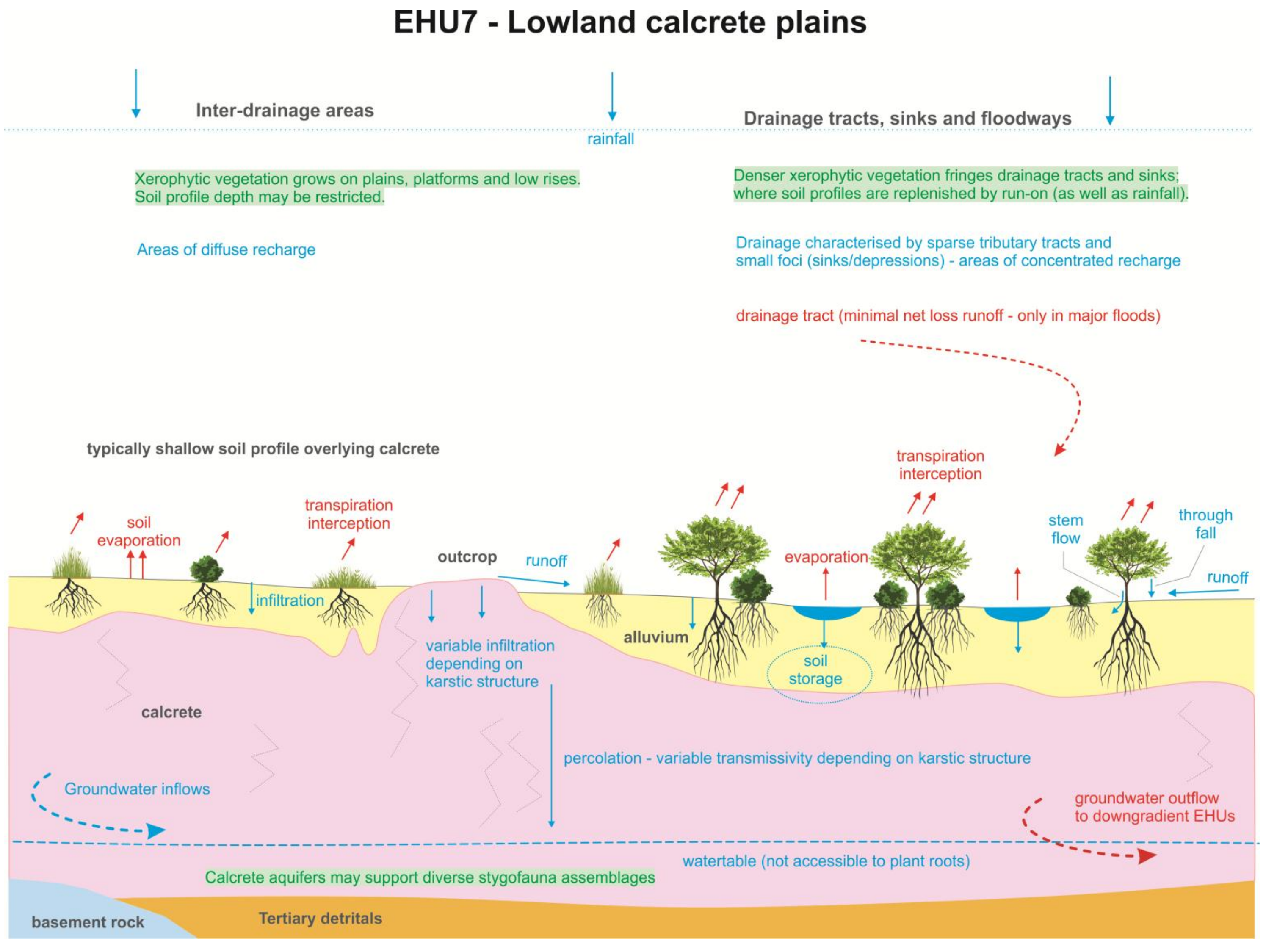


Figure 6 **EHU7 conceptualisation – Lowland calcrete plains**

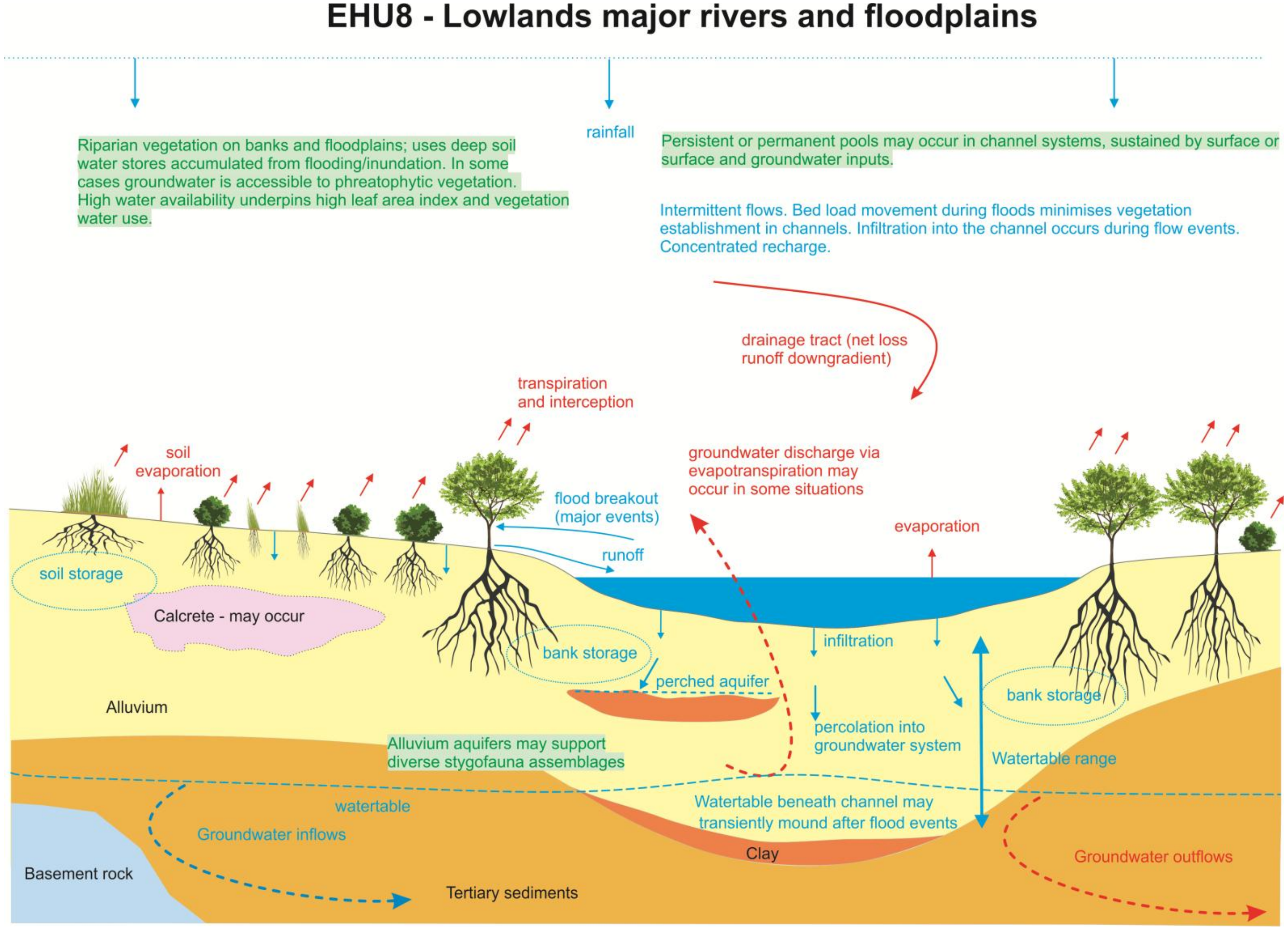


Figure 7 EHU8 conceptualisation – Major rivers and floodplains

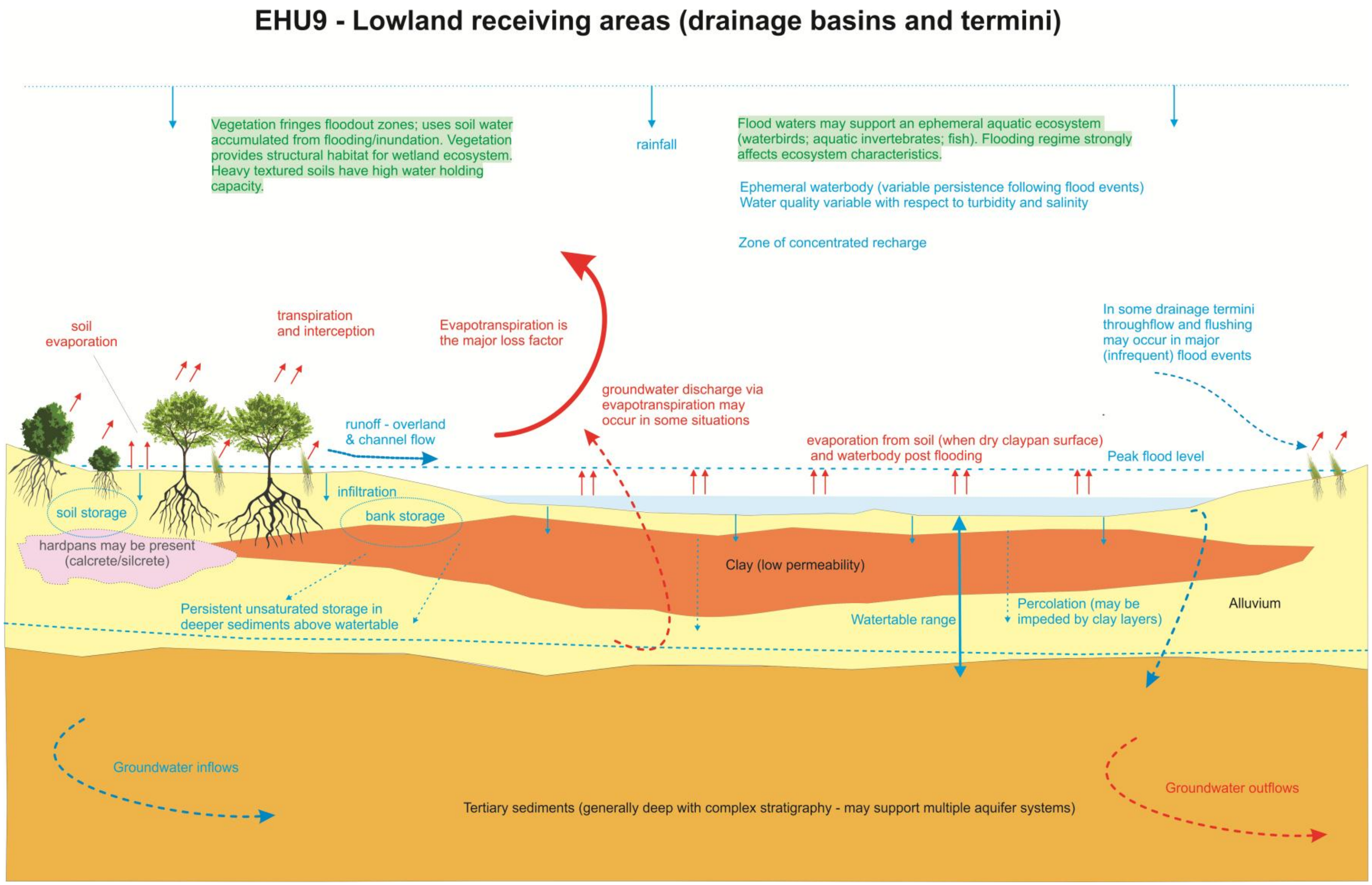


Figure 8 EHU9 conceptualisation - Drainage termini including ephemeral lakes, claypans and flats

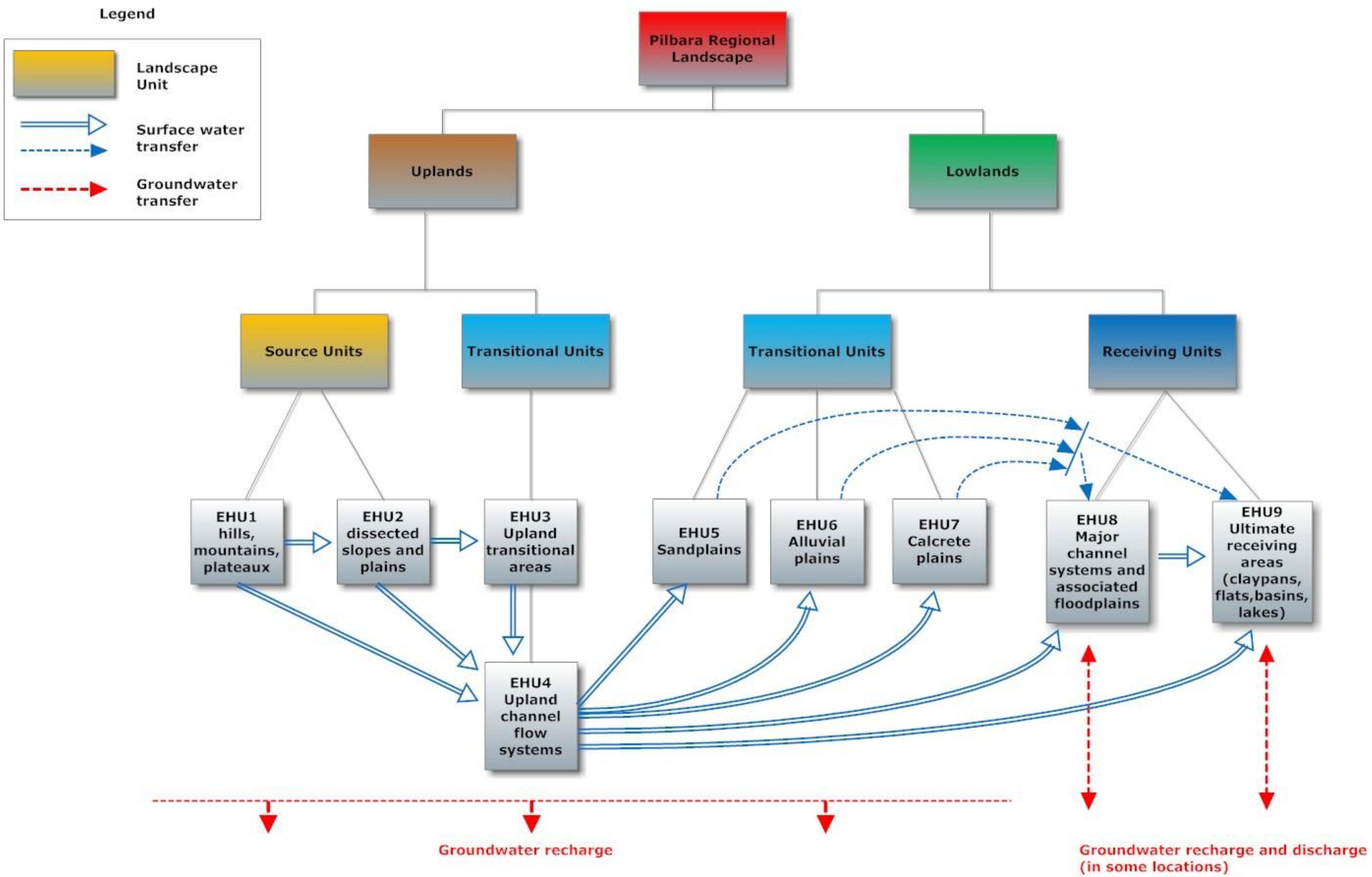


Figure 9 Landscape hierarchy of EHUs and major water flow pathways between them

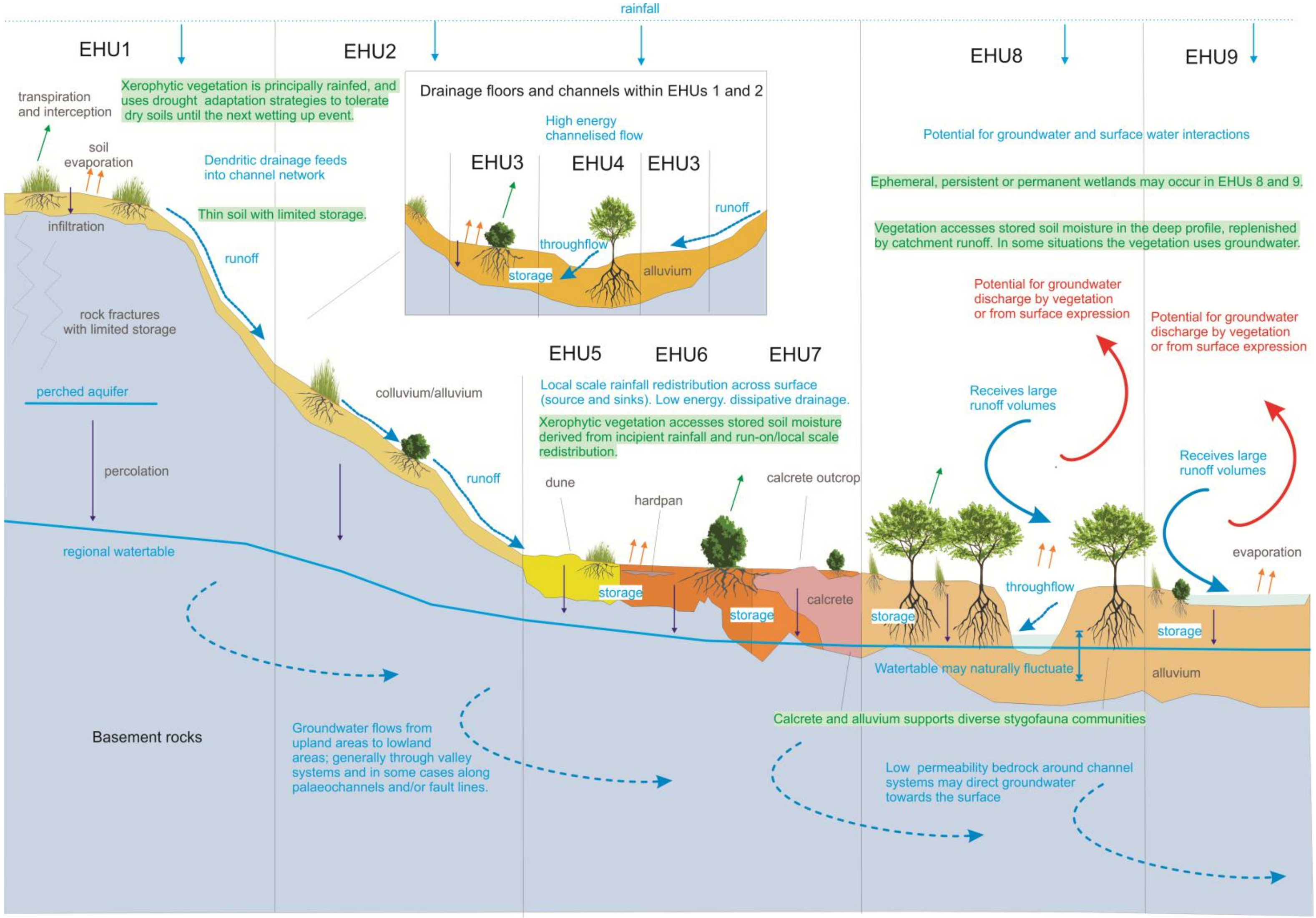


Figure 10 **Landscape arrangement of EHUs**

3 Spatial representation of EHUs

As part of the process of developing the EHUs, it was recognised that approaches for spatial defining EHU boundaries would be required for environmental impact assessment purposes. Priority was placed on using existing spatial datatsets wherever possible. Extrapolation from these datasets, or the development of new datasets, was only undertaken where necessary to achieve adequate resolution of ecohydrological components and processes.

The final datasets selected for spatially defining EHU boundaries included:

- Pilbara land system mapping (Van Vreeswyk *et al.* 2004);
- Surface drainage networks derived using a high resolution (~5 m accuracy) digital elevation model (DEM) provided by BHPBIO;
- Depth to groundwater inferred from existing bore locations;
- Vegetation mapping (leaf area index, structure and dominant species); and
- Landsat NDVI (Normalized Difference Vegetation Index).

The following sections describe the process by which these datasets were interpreted and synthesised in order to define EHUs in each of BHPBIOs project areas. An example of the spatial depiction of EHUs in a representative Pilbara landscape is provided in Figure 11.

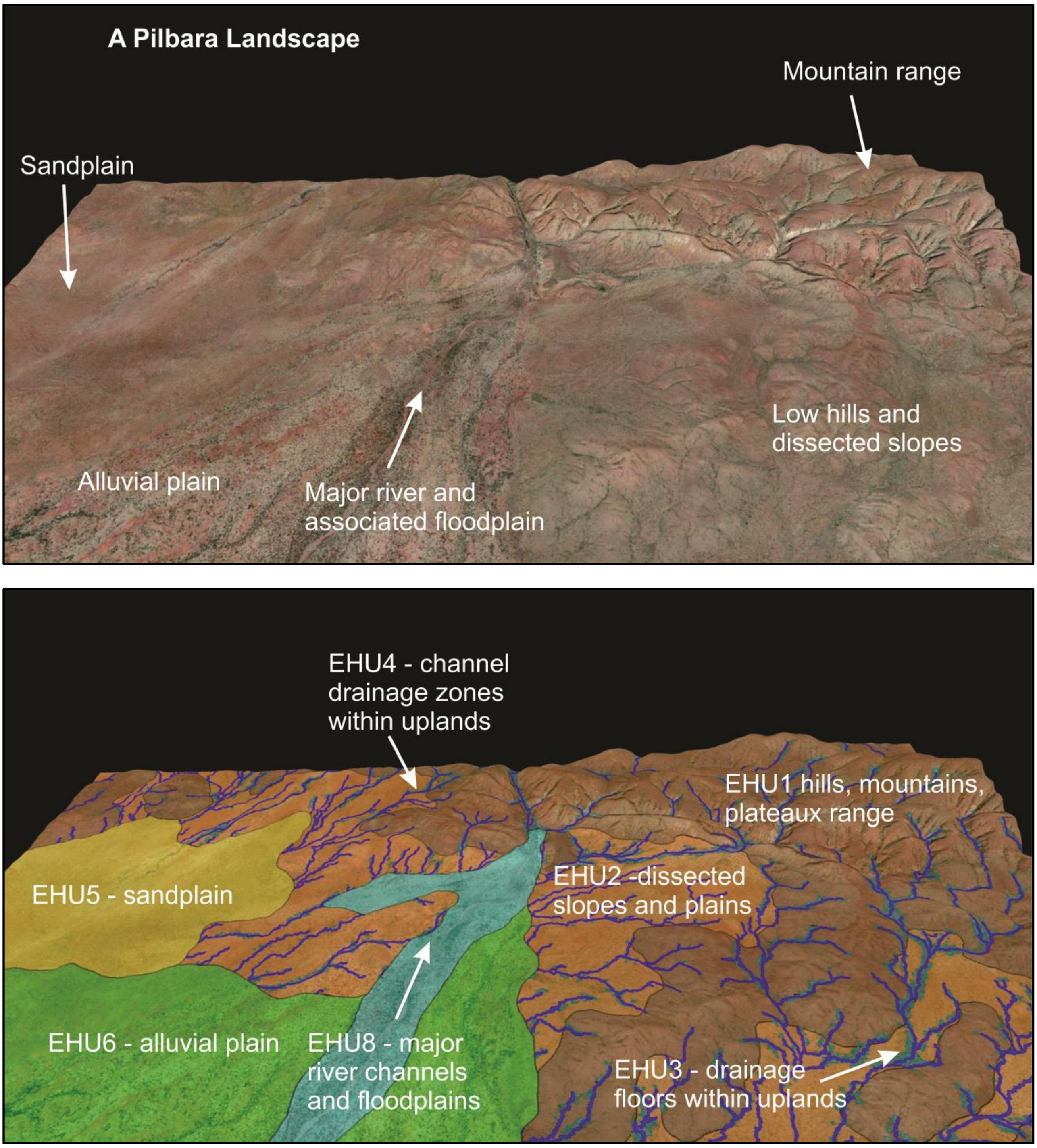


Figure 11 **Example of the spatial depiction of EHUs in a Pilbara landscape**

3.1 Land system mapping

Land system mapping of the Pilbara region was undertaken by the Western Australian Department of Agriculture and Food (DAFWA) during the 1990s for the purposes of land classification, mapping and resource evaluation (Van Vreeswyk *et al.* 2004). Land systems are broadly defined as "areas with a recurring pattern of topography, soils and vegetation". Over 100 land systems are recognised in the Pilbara region.

The Pilbara land system mapping was principally based on interpretation of 1:50,000 aerial photographs, supplemented with other published data (e.g. geology, vegetation and previous land and soil surveys) and relatively limited field observations. This allowed the spatial extent of each land system to be defined. Descriptive information for each land system includes (Van Vreeswyk *et al.* 2004):

- geology;
- geomorphology/landform;
- soils; and
- vegetation - described in three parts:
    - foliar cover
    - formation
    - dominant species

Van Vreeswyk *et al.* (2004) recognised a series of land units within each land system, including estimates of their proportional contribution to the land system spatial extent. Each unit is associated with ecological site types described according to their particular combination of topographic position, land surface, dominant plant species and vegetation formation. An example and a land system description (in this case the Boolgeeda Land System) is provided in Figure 12.

Land system mapping provides a useful basis for developing an ecohydrological conceptualisation of Pilbara landscapes, because by definition the land systems integrate many of the geomorphology, hydrology and vegetation aspects addressed by the EHU classification factors described in Section 2.

Van Vreeswyk et al. (2004) grouped the land systems into 20 land surface types according to a combination of more generic landforms, soils, vegetation and drainage patterns (Table 3). This grouping provides information more suitable for regional scale assessments, and was considered to be highly suitable for classifying different land systems into base EHUs 1, 2, 5, 6, 7, 8 and 9.

Table 3 Land surface types as per an Vreeswyk *et al.* (2004) and corresponding EHU classification

Surface type code	Description of land surface type	Component land systems	EHU classification
1	Hills and ranges with spinifex grasslands	Black, Boolaloo, Capricorn, Granitic, Houndstooth, McKay, Newman, Robertson, Rocklea, Ruth and Talga	**1**
2	Hills and ranges with acacia shrublands	Augustus, Charley and Marandoo	**1**
3	Plateaux, mesas and breakaways with spinifex grasslands	Callawa, Coongimah, Kumina, Nanutarra, Oakover and Robe	**1**
4	Plateaux, mesas and breakaways with acacia shrublands	Laterite and Table	**1**
5	Dissected plains with spinifex grasslands	Billygoat, Egerton and Platform	**2**
6	Stony plains and hills with spinifex grasslands	Adrian, Bonney, Mosquito, Nirran and Tanpool	**2**
7	Stony plains and low hills with acacia shrublands	Collier and Prairie	**2**
8	Stony plains with spinifex grasslands	Boolgeeda, Lochinvar, Macroy, Paterson, Peedamulla, Pyramid, Satirist, Stuart and Taylor	**2**
9	Stony gilgai plains with tussock grasslands and spinifex grasslands	White Springs and Wona	**2**
10	Stony plains with acacia shrublands	Dollar, Elimunna, Ford, Kanjenjie, Paraburdoo and Sylvania	**2**
11	Sandplains with spinifex grasslands	Buckshot, Divide, Giralia, Gregory, Little Sandy, Nita and Uaroo	**5**
12	Wash plains on hardpan with groved mulga shrublands (sometimes with spinifex understorey)	Cadgie, Fan, Jamindie, Jurrawarrina, Nooingnin, Pindering, Spearhole, Three Rivers, Wannamunna, Washplain and Zebra	**6**
13	Alluvial plains with soft spinifex grasslands	Mallina, Paradise and Urandy	**6**
14	Alluvial plains with tussock grasslands or grassy shrublands	Balfour, Brockman, Horseflat, Pullgarah and Turee	**6**
15	Alluvial plains with snakewood shrublands	Christmas, Cowra, Hooley, Marillana, Narbung and Sherlock	**6**
16	Alluvial plains with halophytic shrublands	Cundelbar, Mannerie and Talawana	**6**
17	River plains with grassy	Cane, Coolibah, Fortescue, Jigalong,	**8**

Surface type code	Description of land surface type	Component land systems	EHU classification
	woodlands and shrublands, and tussock grasslands	River and Yamerina	
18	Calcreted drainage plains with shrublands or spinifex grasslands	Calcrete, Lime and Warri	**7**
19	Coastal plains, dunes, mudflats and beaches with tussock grasslands, soft spinifex grasslands and halophytic shrublands	Anna, Cheerawarra, Dune, Eighty Mile, Littoral, Onslow and Roebuck	Not applicable
20	Salt lakes and fringing alluvial plains with halophytic shrublands	Marsh, Lake Bed and Weelarrana	**9**

BOOLGEEDA LAND SYSTEM (7,748 km², 4.3% of the survey area)

(modified from Payne, Mitchell and Holman 1988)

Stony lower slopes and plains below hill systems supporting hard and soft spinifex grasslands and mulga shrublands.

Land type: 8

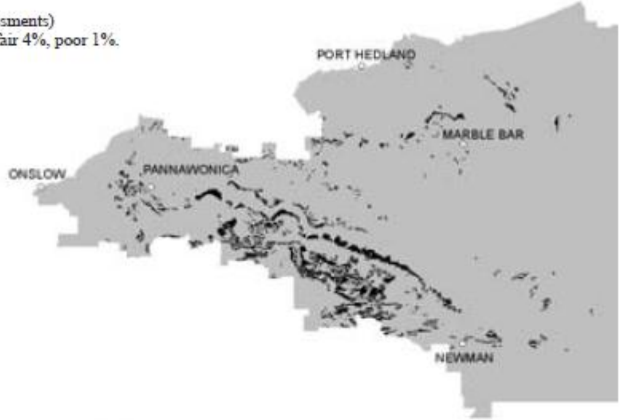
Geology: Quaternary colluvium.

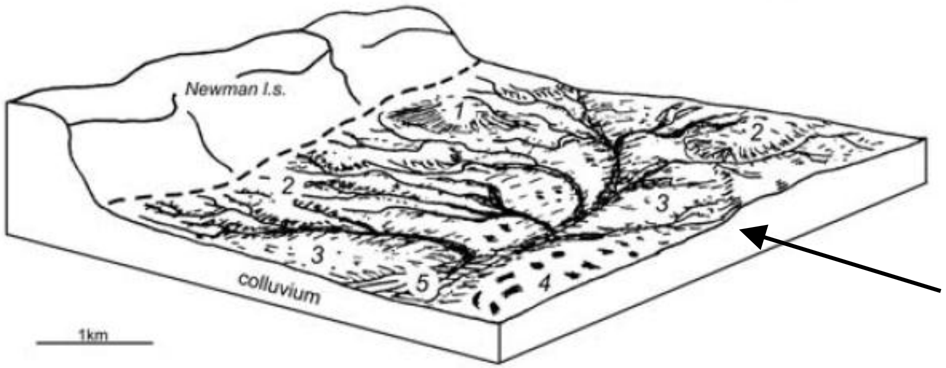
Geomorphology: Predominantly depositional surfaces; very gently inclined stony slopes and plains below hill systems becoming almost level further downslope; closely spaced, dendritic and sub-parallel drainage lines. Relief up to about 20 m.

Land management: Hard spinifex grasslands are not preferred by livestock but soft spinifex is moderately preferred for a few years following fire. Vegetation is generally not prone to degradation and the system is not susceptible to erosion. The system is subject to fairly frequent burning.

Traverse condition summary: (596 assessments)
Vegetation - very good 82%, good 13%, fair 4%, poor 1%.
Soil erosion - nil 100%.

Area mapped as sde: Nil.





Boolgeeda land system

Unit	Area (%)	Landform	Soil	Vegetation
1.	4%	**Low hills and rises** - isolated hills and low rises usually <500 m in extent, surface mantles of very abundant pebbles and cobbles of ironstone, basalt and other rocks; relief up to 20 m.	Stony soils (203) and red shallow loams (522).	Hummock grasslands of *Triodia wiseana* (hard spinifex) and other *Triodia* spp. with very scattered acacia shrubs (HSPG, PHSG).
2.	20%	**Stony slopes and upper plains** - very gently inclined slopes and upper interfluves immediately downslope from adjacent hill systems, dissected up to 5 m by dendritic or sub-parallel small creeklines, surface mantles of common to very abundant pebbles of chert ironstone, quartz and other rocks.	Red shallow loams (522) or red loamy earths (544).	Hummock grasslands of *T. lanigera*, *T. wiseana* (hard spinifex) (PHSG) or scattered tall shrublands of *Acacia aneura* (mulga), *A. ancistrocarpa* (shiny leaf wattle), *A. atkinsiana* and other acacias, occasional eucalypt trees and prominent hard spinifex ground layer (HESG, PMSS).
3.	65%	**Stony lower plains** - almost level plains downslope from unit 2, surface mantles vary from few to very abundant ironstone and other pebbles; subject to sheet and channelised flow from units 1 and 2.	Red loamy earths (544).	Hummock grasslands *T. wiseana*, *T. lanigera* (hard spinifex) or *T. pungens* (soft spinifex) (PHSG, PSSG). Also scattered to moderately close tall shrublands of *A. aneura* and other acacias with hard and soft spinifex ground layer (PHSG, PMSS).
4.	1%	**Groves** - small (up to 20 m long) arcuate drainage foci occurring infrequently on units 2 and 3.	Red loamy earths (544).	Moderately close woodlands or tall shrublands of *A. aneura* with sparse low shrubs and tussock or hummock grasses (GMUW, GMGW, DAHW).
5.	10%	**Narrow drainage floors and channels** - dendritic and parallel flow zones and creeklines on slopes and plains (units 2 and 3), only 5-10 m wide in upper parts becoming wider on lower plains, larger channels may be braided and incised up to 3 m.	Red loamy earths (544) and minor self-mulching cracking clays (602). Channels with river bed soils (705).	Scattered to close tall shrublands or woodlands of *A. aneura*, *A. atkinsiana*, *Corymbia hamersleyana* (Hamersley bloodwood) with sparse low shrubs and hummock and tussock grasses, (DAHW, DEGW, DESG). Occasionally hummock grasslands of *T. pungens* (ASSG).

Land units:

1. Low hill and rise
2. Stony slope and upper plain
3. Stony lower plain
4. Grove
5. Narrow drainage floor and channel

Figure 12 The Boolgeeda land system description reproduced from Vreeswyk et al. (2004). This land system is classified as EHU2.

3.2 Surface drainage derived from DEM

A 5 m digital elevation model (DEM), commissioned by BHPIO was available for interpretation of EHUs. The DEM coverage included the majority of the four BHPBIO project areas, but with some gaps around the project area margins. For the areas outside of the 5 m DEM extent, a 30 m DEM was sourced from Geoscience Australia.

The DEM data enabled high resolution topographical and drainage interpretation in order to delineate EHU4 units within the broader EHU 1 and EHU 2 upland units. The hydrological tools of the Spatial Analyst (ESRI) were used to identify and apply a Strahler stream order classification to drainage lines interpreted from the DEM. Inspection of the derived drainage networks against aerial photography and BHPBIO vegetation mapping indicated that higher order streams were suitable for classifying as EHU 4 units. The drainage lines were buffered by 10 m to create EHU 4 polygons.

3.3 Landsat NDVI

Landsat Normalized Difference Vegetation Index (NDVI) imagery was used to better define upland transitional and receiving areas (EHUs 3 and 4). NDVI is a normalized ratio calculated from reflected radiation in the red and near-infrared spectral regions[1]. NDVI is highly correlated with active plant leaf surfaces (such that it is sometimes referred to as a 'greenness' index) and therefore provides an indication of vegetation density and growth dynamics.

NDVI has been found to provide a basis for linking vegetation and soil moisture dynamics in dryland environments (Chen *et al.* 2014). Water storage and NDVI have been shown to be significantly correlated across Australia (MacGrath *et al.* 2012). In the Pilbara high NDVI values typically lag high soil moisture conditions by about one to two months (Chen *et al.* 2014). It follows that high NDVI is a potential indicator of areas where water is stored and used by vegetation, as anticipated to occur in EHUs 3 and 4.

To test the utility of using NDVI to spatially depict EHUs 3 and 4, several Landsat NDVI tiles were obtained from the National Oceanic and Atmospheric Administration (NOAA) to generate GIS overlays:

- Imagery acquired in September-October 2001.
- Imagery acquired in March 2008.
- Imagery acquired in March 2009.

In each case areas of high 'greenness' were defined where NDVI ≥0.11; considered to be an appropriate threshold for relatively sparse vegetation types as generally encountered in the Pilbara. Visual inspection of the high NDVI areas suggested that the September-October 2001 dataset was the most appropriate for defining EHUs 3 and 4. This image was acquired after monthly rainfall of about 20 to 30 mm was received in July 2001 across BHPBIO's study areas, preceded and followed by little rain. The antecedent rainfall was therefore consistent with the temporal lag of one to two months identified by Chen *et al. (*2014). For the March 2008 and 2009 images, relatively large amounts of rainfall in the preceding summer months appeared to obscure patterns between topography and greenness in upland settings.

Using the interpretation from the September-October 2001 dataset, areas of high 'greenness' were strongly associated with drainage lines identified from the high resolution DEM. Based on topography and aerial photograph interpretation, additional zones of high greenness were generally well matched with drainage floors abutting the EHU4 units. Spatial Analyst (ESRI) was therefore used to define EHU 3 areas as zones of high greenness (NDVI ≥0.11) within 50 m of the EHU4 units (as defined in Section 3.2).

[1] NDVI values may vary between -1.0 and +1.0.

Note that the approach for defining EHU3 was selected to provide adequate regional scale coverage across BHPBIOs project areas, within the time and resources available for this task. A variety of approaches for more sophisticated EHU delineation using NDVI and other remote sensing products are available, including time series analysis of multiple images and spectral indices. BHPBIO may wish to explore these approaches further in future iterations of EHU development and spatial definition.

3.4 Depth to groundwater

The ECM development process for each BHPBIO project area involved the derivation of water level contour maps based on available bore water level records. The generated depth to groundwater maps were overlaid with the base EHU layers to explore correlations between zones of shallow groundwater and different EHUs.

This analysis indicated that zones of shallow groundwater (<10 m) were correlated with major river systems EHU8 and the Fortescue Marsh (EHU9). Around the Fortescue Marsh a zone of relatively shallow groundwater (5 to 10 mbgl) was inferred to extend into portions of the surrounding alluvial and calcrete plains (EHUs 6 and 7). In some cases zones of shallow groundwater were inferred to occur in association with channel zones further upgradient from areas corresponding with Land Surface Type 17 (van Vreeswyk *et al.* 2004).

These areas may warrant more detailed investigation; for example with respect to the interpolation of groundwater depth, particularly where the bore network is sparse. In some cases, in combination with vegetation mapping data, inferred zones of shallow groundwater provided the basis for extending EHU8 zones further upstream (refer to Section 3.6).

3.5 Vegetation mapping

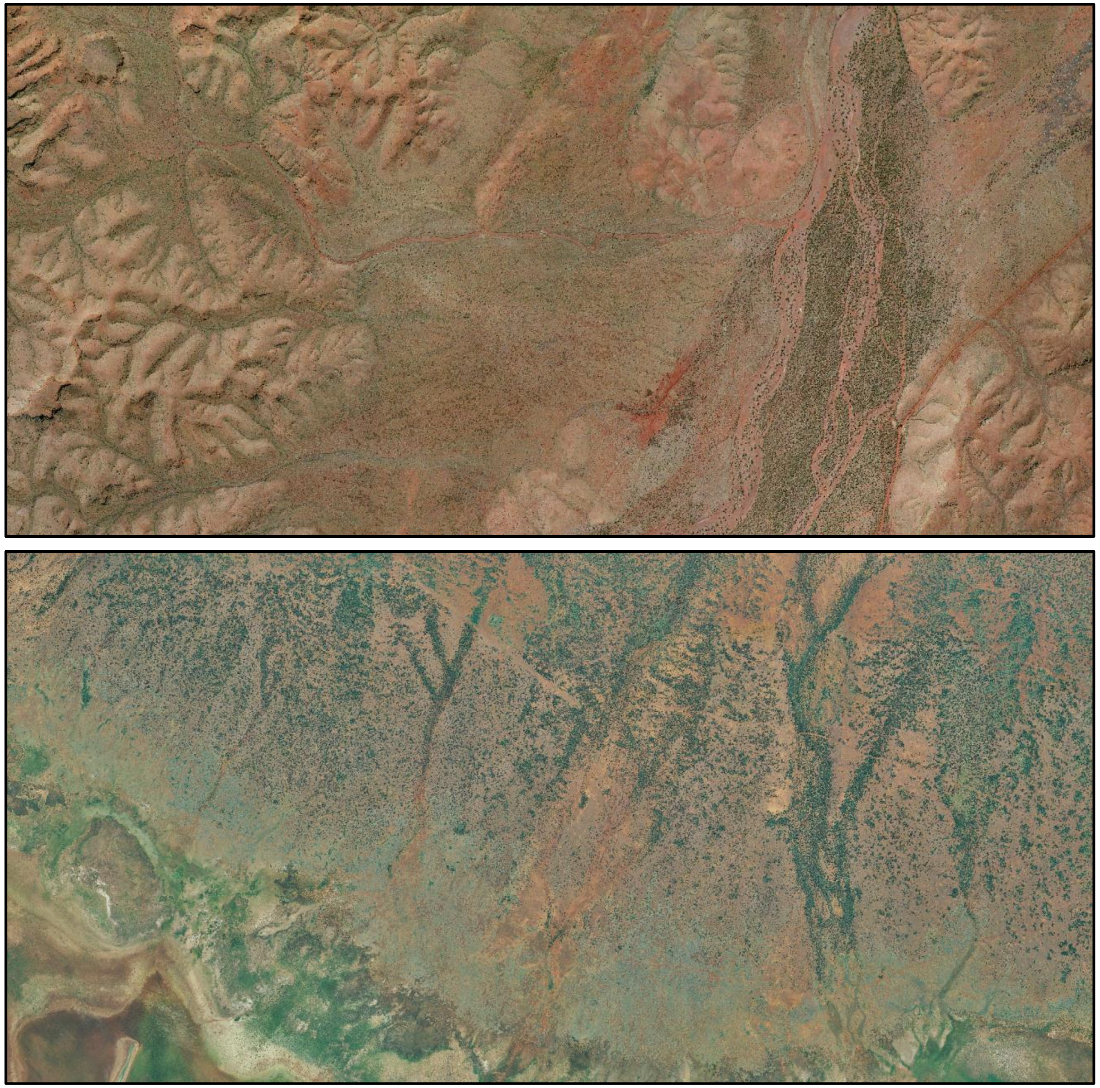
In arid and semi-arid regions, the interaction and feedbacks between climate, soils, vegetation and topography give rise to distinct patterns of vegetation and surface water re-distribution. These patterns in turn are determinants of many other ecosystem attributes. As such, patterns of vegetation can provide information about ecohydrological processes. For example, banded vegetation formations are generally considered to be associated with zones of sheetflow. In the central Pilbara these areas typically occur in broad inter-drainage areas on alluvial plains near the base of hills and ranges. Major channels often host *Eucalyptus* forest and woodland communities, which are sustained by inflows combined with deep soils that can store large volumes of water.

Leaf area index (LAI) is a useful indicator of water availability for vegetation, consistent with the principle of ecological optimality (O’Grady *et al.* 2011; Ellis & Hatton 2008). This principle states that over long time scales vegetation in water limited environments will equilibrate with climate and soils to optimally use the available soil water. As a consequence high LAI is typically correlated with zones of water accumulation via landscape connectivity pathways, such as areas with deep soil profiles (i.e. large water storage capacity) combined with surface or sub-surface lateral inflows; and/or areas with relatively fresh, shallow groundwater accessible to vegetation root systems.

At a landscape scale LAI can be interpreted using aerial photography. Visual examples of areas of high LAI associated with water gaining areas are provided in Figure 13; highlighting relationships between vegetation LAI and patterns of drainage. Areas that persistently maintain high LAI relative to surrounding vegetation are more likely to have access to (and a dependency on) groundwater. However, it is important to recognise that LAI is a dynamic vegetation characteristic influenced by climate and disturbance events such as fire and grazing. Seasonal effects may also be important. Therefore some caution is required when interpreting LAI observations.

Large areas of BHPBIOs project areas have been subject to vegetation mapping, with a focus on describing vegetation structure and floristic components. Vegetation mapping units produced from these ground based surveys usefully augment land system mapping units (van Vreeswyk *et al.* 2004), by providing greater resolution of vegetation patterns and the occurence of key indoicator species (such as the phreatophytic tree species *E. camaldulensis* subsp. *refulgens*, *E. victrix* and *Melaleuca argentea)*.

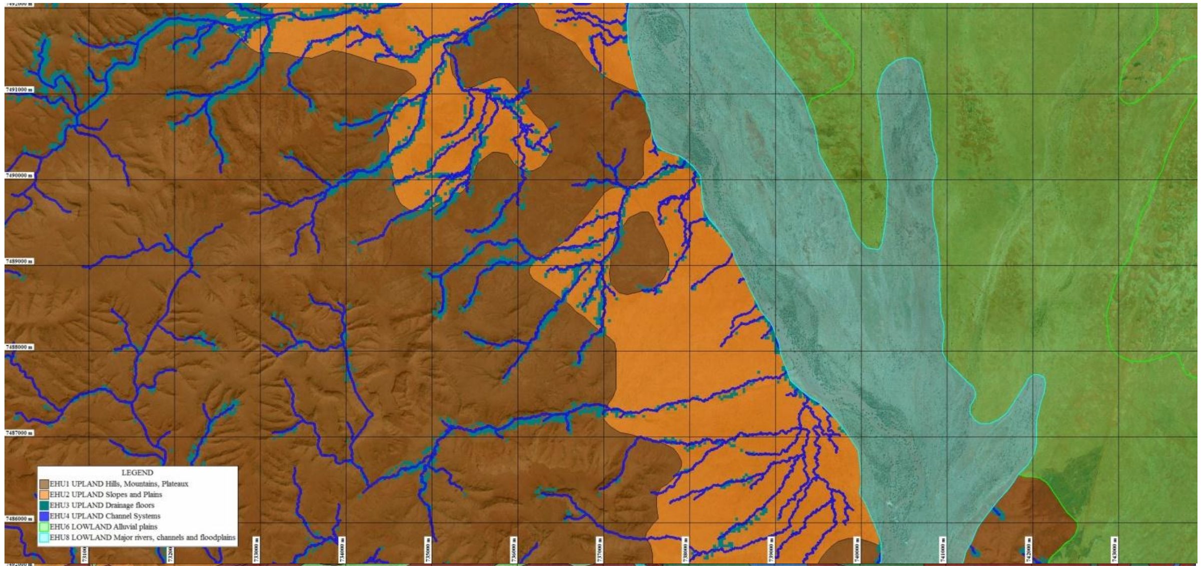
Overlays of vegetation mapping units on land surface types (Table 3), drainage lines (Section 3.2) and zones of high NDVI (Section 3.3) were used for testing and validating inferred relationships between landscape hydrology and vegetation patterns, including inferred vegetation ecohydrological function. This was augmented by aerial photography interpretation. Validation assessments were undertaken in various portions of BHPBIOs project areas where vegetation mapping was available, spanning the full suite of defined EHUs. The findings generally supported the approach used for spatially defining EHUs. Examples of some of the validation overlays are provided in Figure 14 and Figure 15.



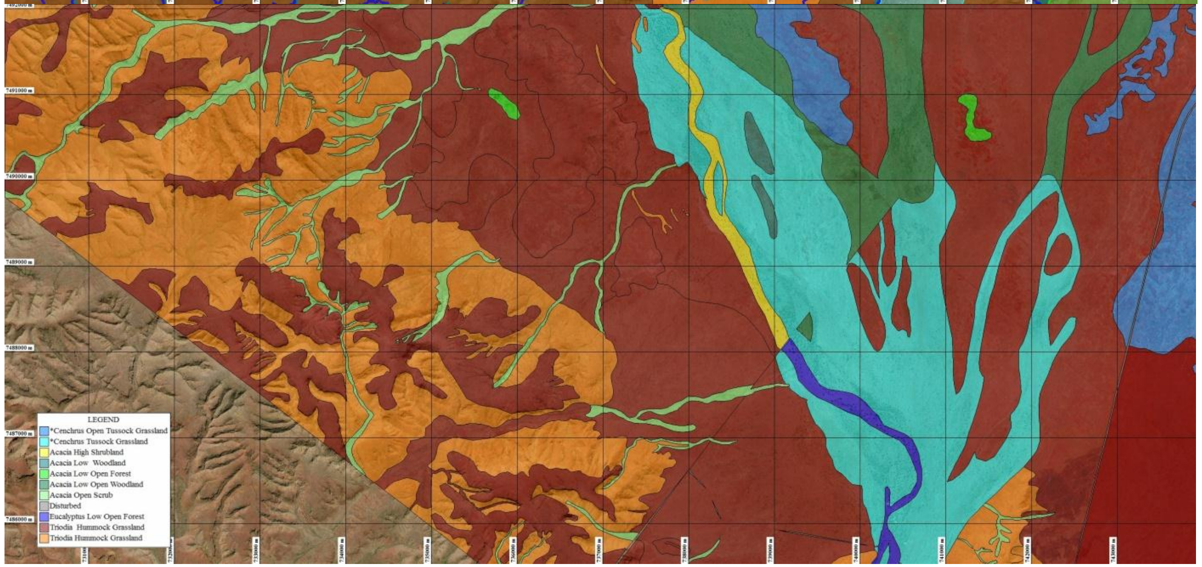
Lower Weeli Wolli Creek. Note the concentration of vegetation in dendritic drainage lines (LHS), and relatively dense *Eucalyptus* woodland along the Weeli Wolli Creek floodplain (RHS).

The north west margin of the Fortescue Marsh. Note *Acacia* woodland concentrated along drainage lines north of the Marsh (top), with some banded formations in the interdrainage areas. At the boundary of the Marsh (bottom) denser vegetation is associated with drainage outlets.

Figure 13 Examples of vegetation with high leaf area index (LAI) in water gaining areas

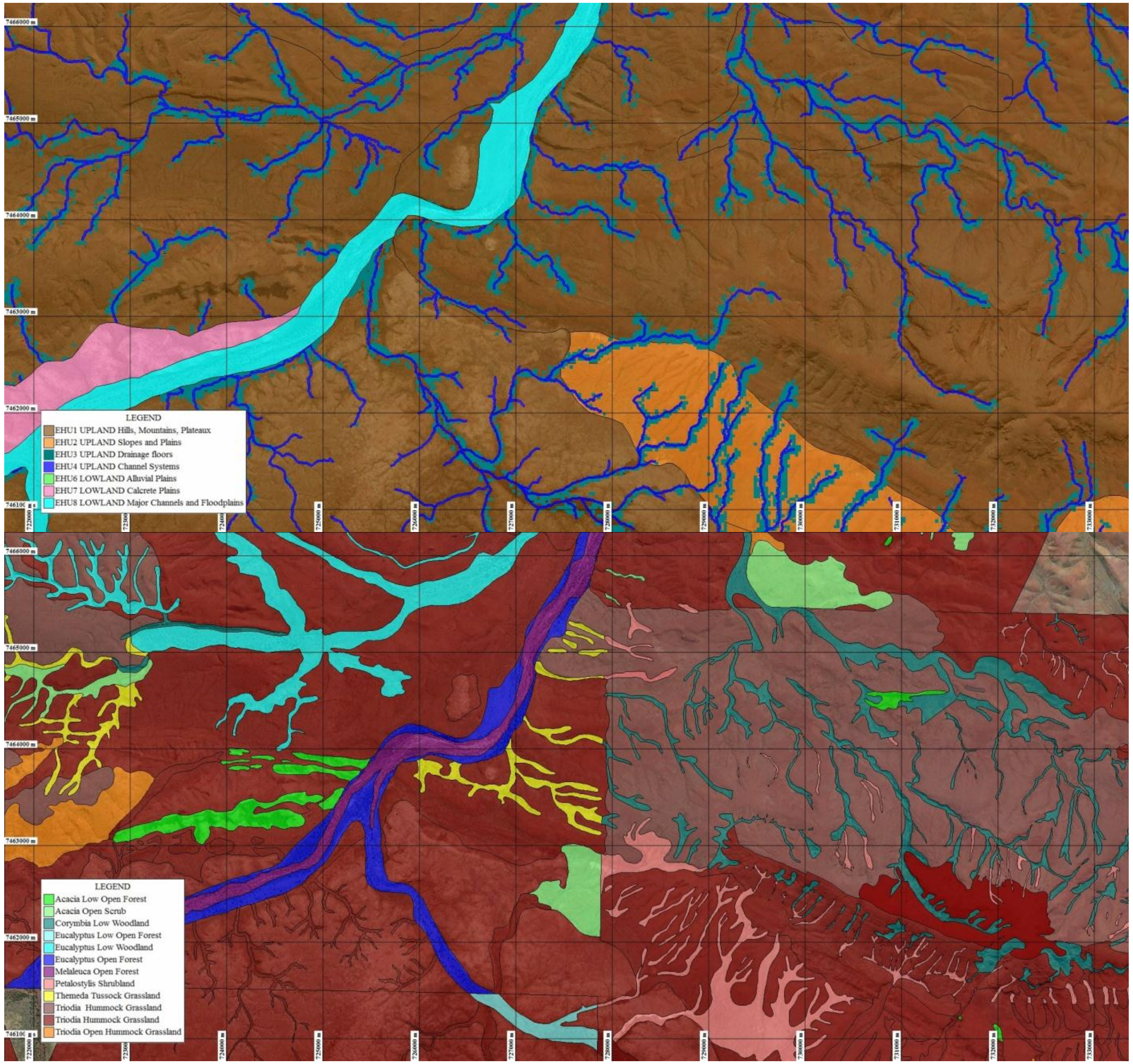


EHUs near the lower reaches of Weeli Wolli Creek as it exits the Hamersley Range.



BHPBIO vegetation mapping units near the lower reaches of Weeli Wolli Creek as it exits the Hamersley Range. Note that EHUs 1 and 2 are dominated by *Triodia* spp. hummock grasslands (two types). EHUs 3 and 4 are correlated with *Acacia* scrub. EHU6 predominantly includes a mix of hummock grasslands and *Acacia* woodlands along drainage tracts. EHU8 includes **Cenchrus* tussock grasslands (with scattered *Eucalyptus victrix*), a section of *Eucalyptus* low open forest (*E. camaldulensis* subsp. *refulgens* and *E. victrix*), and patches of *Acacia* woodlands.

Figure 14 Example 1 of the alignment between EHUS and BHPBIO vegetation mapping units



EHUs in the vicinity of Weeli Wolli Spring and surrounding landscapes.

BHPBIO vegetation mapping units in the vicinity of Weeli Wolli Spring and surrounding landscapes. Note that EHUs 1 and 2 are dominated by *Triodia* spp. hummock grasslands (three types). EHUs 3 and 4 are correlated with *Corymbia* and *Eucalyptus* woodlands and forests, and tussock grasslands. EHU7 inlcudes hummock grasslands, in this case two types also found in EHUS 1 and 2. EHU8 may include open forests dominated by *Eucalyptus* and *Melaleuca* species.

Figure 15 Example 2 of the alignment between EHUS and BHPBIO vegetation mapping units

3.6 Additional adjustments to EHU polygons

Once a set of base EHU polygons was developed through the synthesis of the aforementioned datatsets, some additional adjustments to the polygons were made at the BHPBIO region level in order to account for local area ecohydrological features requiring higher resolution delineation. These adjustments are summarised as follows:

Fortescue Marsh region

Additional EHU 9 areas, as sub-areas within the broader land surface type units of Van Vreeswyk *et al.* (2004), were defined using:

- Quaternary lucustrine (Ql) 1:250,000 geology mapping units; and
- DPaW polygons depicting claypans associated with the Freshwater Claypans of the Fortescue Valley PEC.

These alternative mapping units provided improved resolution of landscape drainage termini, by separating out small basins and depressions within alluvial plains (EHU6), calcrete plains (EHU7) and river floodplains (EHU8) south and west of the Fortescue Marsh.

Central Pilbara region

In this project area the lower reaches of Weeli Wolli Creek and its associated floodplain (EHU8) are represented by the River Land System mapped by van Vreeswyk *et al.* (2004). This EHU8 mapping unit was extended upstream to a point near Ben's Oasis, based on aerial photography interpretation of the Weeli Wolli Creek and floodplain landform (including riparian vegetation communities), BHPBIO vegetation mapping units including the phreatophytic species *E. camaldulensis* subsp. *refulgens*, *E. victrix* and *Melaleuca argentea* (available for some creekline section), and depth to watertable information.

The Coondewanna Flats, which hosts the ephemeral Lake Robinson, is a zone of terminal drainage within the more widely distributed Wannamunna Land System classified as land surface tyoe 12 by van Vreeswyk *et al.* (2004) and therefore nominally EHU6. Examination of the geomorphological and hydrological setting of Lake Robinson and fringing areas suggested that this area has features more consistent with EHU9. This area is broadly coincident with the *Eriachne* sp. Tussock Grassland vegetation mapping unit delineated in BHPBIO vegetation mapping of the Coondewanna Flats area. Consequently the *Eriachne* sp. Tussock Grassland vegetation mapping unit was overlaid as an EHU9 zone.

Marillana Creek region

In this project area the lower reaches of the Marillana Creek and its associated floodplain (EHU8) are represented by the River Land System mapped by van Vreeswyk *et al.* (2004). This EHU8 mapping unit was extended upstream to approximately 7 km upstream of Flat Rock gauging station, based on aerial photography interpretation of the Marillana Creek and floodplain landform (including riparian vegetation communities), BHPBIO vegetation mapping units including the phreatophytic species *E. camaldulensis* subsp. *refulgens*, *E. victrix* and *Melaleuca argentea*, and depth to watertable information.

The Munjina Claypan is a surface basin feature broadly coincident with the Brockman Land System, classified as land surface type 14 by van Vreeswyk *et al.* (2004) and therefore nominally EHU6. Examination of the geomorphological and hydrological setting of the Munjina Claypan suggested that this area has features more consistent with EHU9, and therefore the Brockman Land System in this setting was reclassified to EHU9.

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