Dryland Landscapes

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New A Level Subject Content Overview

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Introduction

Drylands cover 40-50% of Earth's terrestrial surface and are home to around a third of the world's population. It is important to be aware that most geomorphological processes operate to some degree in dryland environments but what separates dryland from humid landscapes are the direct and indirect effects of limited water availability.

Table 1 shows how four dryland (or 'arid') zones can be identified based on moisture balance – the ratio between moisture input (precipitation - P) and moisture output (potential evapotranspiration - PET). These four zones are mainly located in tropical and temperate latitudes. An additional fifth zone encompasses cold, dry regions located in high latitudes.

Table 1: *Classification of drylands based on the UNEP Aridity Index (1997)*

Description	Aridity Index (UNEP, 1997) P/PET	Area of Earth's Surface	Approximate average annual precipitation
Hyper-arid	<0.05	10 million km^2	<50 mm
Arid	0.05-<0.2	16 million km^2	50-250 mm
Semi-arid	0.2-<0.5	23 million km^2	250-500 mm
Dry sub-humid	0.5-<0.65	13 million km^2	-
Cold arid	-	5 million km^2	<250 mm

There are four main factors that contribute to the global distribution of drylands two of which operate at the global scale, and two of which are regionally-controlled.

1. At the global scale the first cause of drylands is the behaviour of large-scale air masses. Descending, stable warm air associated with tropical high-pressure belts, and cold, dry subsiding air at the North and South Poles lead to low and highly variable rainfall in these regions (e.g. Sahara).
2. The second contributing factor is 'continentality' – as air masses move from the oceans overland they lose moisture as rainfall and consequently distance from the ocean is important (e.g. in central Asia).

3. At the regional scale, high mountain ranges such as the southern Andes, Sierra Nevada and Great Dividing Range can generate rain-shadow and respectively contribute to the presence of the Atacama, Californian and Australian deserts.
4. Also at the regional scale evaporation from cold ocean currents, such as the Humboldt (South America) and Benguela (southern Africa) is very low causing adjacent coastal areas to receive little precipitation. However, where cool ocean air and warm air overland combine; this can result in coastal fog that typifies some deserts such as the Atacama (Figure 1) and the Namib. The geographical distribution of dryland landscapes is therefore controlled by large scale global climate and topography.

a) b)

Figure 1: (a) *Fog forms along the coastal margin of the Atacama Desert, South America when cold air over the ocean combines with warm continental air. (b) Fog-dependent vegetation, Tillandsia landbeckii, in the northern Atacama Desert. © Professor Joanna Bullard*

The geomorphological characteristics of Earth's drylands vary considerably (Table 2, Figure 2). A common misperception of dryland landscapes is that they are dominated by sand dunes but in fact, dunes cover only 20-25% of drylands. The main types of dryland geomorphology are:

- *Mountain-Basin regions*: these have high relative relief controlled by geology, and bedrock is exposed. They make up about 40% of the land surface of the Saharan, Arabian and south-western USA dryland regions. Death Valley in the USA is an example where mountains over 2000 m high are found adjacent to salt flats below sea level.
- *Piedmonts*: these are transitional areas between the uplands and lower areas and are characterised by depositional (e.g. alluvial fans) and erosional (e.g. pediments) landforms.
- *Stony Deserts*: these generally have low relative relief and comprise stony plains and structural plateaux. Stony deserts, also known as reg or gobi, are largely vegetation-free and are often characterised by the development of stone pavement – a high density of coarse particles at the surface overlying a finer soil. Approximately 40% of the drylands of China are stony (gobi) deserts.
- *Ephemeral rivers, floodplains and dry lake basins*: these areas are normally dry but during occasional, often high intensity but short duration, rainfall events they can be inundated by large flows of water and sediment. Floodwaters may be generated within the dryland region (known as endogenic drainage) or from precipitation outside the desert, but that flows into it (known as allogenic drainage).

- *Sandy deserts*: sandy deserts can comprise expansive areas without dune forms (sand sheets) or sand can be blown by the wind to form dunes. Some dryland areas have extensive dunefields (also known as sand seas), for example Australia, southern Africa, Arabian Peninsula, Sahara, whereas others, such as the USA, have only very small, isolated dunefields.

Figure 2*: a) Stone pavement, Jordan, b) Mountain-basin landscape with alluvial fans and salt flat, Death Valley, SW USA (photograph courtesy of Ian Livingstone), c) Sand dunes, Atacama Desert, Chile, d) Dry lake bed, Central Australia. e) The Grand Canyon, SW USA (photograph courtesy of David Nash), f) River channels, Central Australia. © Professor Joanna Bullard*

Table 2: *Percentage area of dryland landscape types in the SW USA, Sahara and Arabia (*adapted from Goudie, 2002).

Landform type	SW USA	Sahara	Arabia	Australia
Desert mountains	38	43	47	16
Alluvial fans	31	1	1	0
Low angle bedrock and stony deserts	1	10	1	14
Rivers, floodplains and channel systems	5	2	4	13
Badlands	3	2	1	0
Playas (dry lakes)	1	1	1	1
Sand dunes	1	28	26	40
Undifferentiated desert flats	20	10	16	16

2. Key geographical concepts and concerns and an introduction to the theoretical underpinning of them

Dryland landscapes at A Level are included within the Landscape Systems theme. The systems approach to understanding geomorphology puts an emphasis on transfers of mass and energy among components within the system, and also with the external environment. It puts a focus on how component parts of the system are linked and what is the impact of changes in flows and storage of material over time. This is known as a process-response system. A simple conceptual model of a process-response system is shown in Figure 3. The flow (e.g. water or wind) causes sediment to be transported which creates a landform. Once in place the landform can affect the flow, for example if flow is constricted such as between channel banks, it will increase in speed. The increased flow will be able to transport more sediment and so cause a change to the landform, e.g. eroding and deepening the channel. Using the example of a sand dune, wind (flow) will transport sand (sediment) to create a dune (form). In the early stages of landform development this will be a positive feedback loop so that through the continued action of the wind, more sediment will be transported to create a larger dune. However the form of the dune can also affect the wind flow so that at some point (which will be locally variable) no more sediment will be deposited at the top of the dune and it will reach equilibrium. The whole system can also be affected by environmental factors such as climate, geology, tectonic activity or human influence. A change in one or more of these factors can lead to gradual (e.g. climate change) or sudden (e.g. earthquake) changes in the amount of sediment available for transport, or the efficiency of flow.

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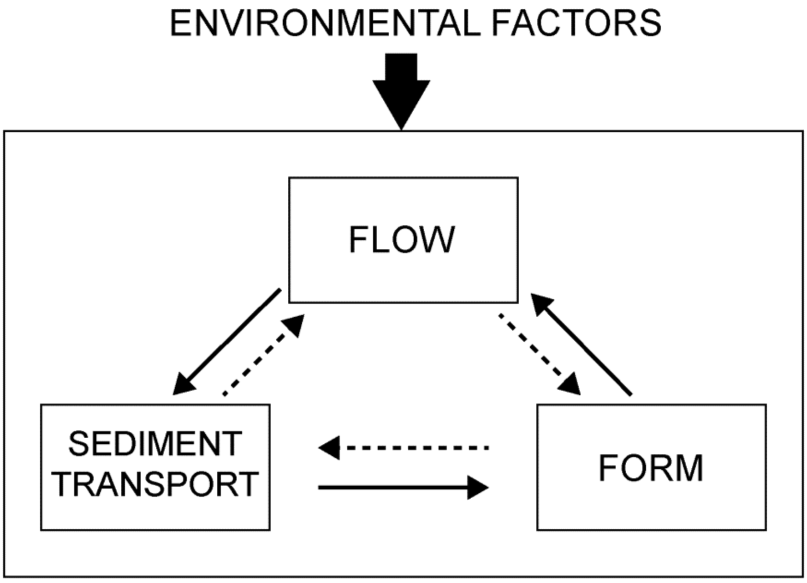

Figure 3: *Generalised feedback system between flow, geomorphic form and sediment transport.*

3. Subject Content

A. Knowledge and understanding of dryland landscapes

The introduction outlined what basic knowledge is needed to understand what drylands are, where they occur and some of the different types of dryland landscape. This section highlights some key processes and landforms that characterise dryland landscapes and considers how these might be addressed in taught sessions.

Weathering

Mechanical weathering, the disintegration of rock caused by physical rather than chemical processes, is important in dryland landscapes. The lack of moisture restricts the quantity and permanence of vegetation and this lack of vegetation cover, combined with high daily (diurnal) temperatures ranges, exposes sediments to extremes of temperature. For example ground surface temperatures can exceed 70°C with diurnal ranges in excess of 50°C. This exposure can mean that local geology is a more important control of weathering and sediment production than in humid environments. Two types of weathering dominate. The first is insolation weathering which is rock breakdown as a result of daily expansion and contraction of rocks in response to stresses cause by temperature gradients. Originally insolation weathering was thought to occur solely in response to rock thermal expansion but it is now thought likely that small amounts of moisture (e.g. from fog or dew) contribute to the process.

The second type of weathering is salt weathering. Salt weathering occurs when salts accumulate, rather than being washed away by rainwater, and exert stresses on rocks through crystallisation (salt crystal growth), hydration or thermal expansion. Salt weathering can cause rapid disintegration of rocks in situ, and also causes damage to buildings and infrastructure in dryland regions. Other types of weathering that can occur in drylands are frost weathering and biological weathering.

Weathering can cause distinctive landforms such as cavernous weathering features and tafoni (honeycomb) to form. It is also an important process in the formation of pediment-inselberg landscapes. Weathering causes the breakdown of rocks in to small particles that can then be transported by wind, water.

Role of water

As shown in Table 1, total annual rainfall is low in dryland regions. Rather than occurring as small amounts of input throughout the year, rainfall in drylands is often very seasonal occurring as a limited number of low frequency, high magnitude or high intensity events. The sparse vegetation cover in drylands leaves extensive areas of unconsolidated fine sediments unprotected at the desert surface and this lack of protection can mean that when rainfall events do occur they result in rapid erosion leading to high sediment loads in some dryland rivers. In many desert landscapes the presence of surface water is ephemeral (short-lived) but groundwater may be present.

Ephemeral river channels in deserts are often referred to as wadis. Arroyos (rectangular cross-section) and gullies (v-shaped cross-section) are particular types of channel. Alluvial fans form at the interface between a mountain front and a lower depositional area. They are not unique to desert areas but can form very dramatic landscapes (Figure 2b) and are particularly prominent in the deserts of the tectonically-active SW USA (Table 2). The Colorado Plateau, also in the SW USA, is a well-known desert fluvial landscape. It derives its name from the Colorado River which drains 90% of the plateau and which has eroded the distinctive Grand Canyon by down-cutting over the past 5-6 million years (Figure 2e).

A particular feature of some deserts are dry lakes which are thought to cover 1% of the desert landscape. These are known as ephemeral lakes, pans, playas or salt lakes. Most lake surfaces in deserts are vegetation free due to an accumulation of salt at the surface. When filled by seasonal rains, these features can be important temporary water sources for humans and animals. They can also have economic importance as some desert lakes are mined for salt.

Role of the wind

The lack of vegetation means wind can be a more effective geomorphological agent in drylands than in some more humid landscapes. Wind transports sand-sized sediments (0.063-2 mm diameter) close (typically within 2 m) to the ground surface. When deposited, the sand creates landforms such as sand sheets, dunes and dunefields. Sand sheets generally comprise coarser sands than dunes. There are many different dune types. The main dune types in areas with no, or sparse, vegetation are controlled by how variable the wind regime is, and how much sand is available for dune building (Table 3). Ripples, the smallest aeolian bedform, form on upwind dune slopes and on sand sheets.

Table 3: *Main characteristics of four dune types*

Dune type	Wind regime	Sand supply	Location
Barchan	Wind from a single direction	Low	Margins of dunefields
Transverse	Wind from a single, or narrow range, of directions	Medium	Anywhere in a dunefield; 30-40% of Saharan dunes are transverse. Dominant dune type in the USA.
Linear	Typically wind from two different directions (seasonal)	Medium	Anywhere in a dunefield; 99% of Kalahari and Australian desert dunes are linear.
Star	Wind from three or more different directions	High	Centres of dunefields; star dunes make up 18% of the Namib dunes.

In addition to creating landforms of deposition, the wind can also erode the landscape. A ventefact is a stone or boulder that has been shaped by the wind (Figure 4a). Ventefacts are common in polar deserts as well as sub-tropical deserts. Larger wind-eroded landforms are typified by yardangs (Figure 4b). Yardangs are stream-lined erosional forms created by the wind erosion of materials including rock (such as sandstone, granite) and sediment deposits (such as lake sediments). Yardangs are not common in deserts as they require very dry conditions and persistent winds from a single direction. The Lut Desert, Iran contains a distinctive yardang field.

a)

b)

Figure 4: a) *Ventefact, Mojave Desert, USA. This ventefact is c. 50 cm height. b) Yardangs, northern China. The yardang in the foreground is approximately 10 m high. © Professor Joanna Bullard*

Wind erosion can also cause deflation – the removal of fine material from a surface. The process of deflation contributes to the occurrence of dust storms and can is also important in the formation of stone pavements. The largest global dust source – The Bodélé

Depression – is the now dry Lake Chad in North Africa. Although they have been discussed separately here, it is worth noting that there are links between weathering, wind (aeolian) and water (fluvial) systems in drylands. In particular, weathering produces the material, fluvial systems transport and deposit it, the wind piles it up, or removes it to create landforms.

B. Systems framework – focusing on transfers of energy and movement of materials

In order to understand the desert landscape and landforms within it, it is important to understand the processes responsible for their formation.

As highlighted in section 1, understanding the global scale distribution requires some knowledge of **global climate systems** and the locations where air is subsiding or rising. Global ocean and wind circulation patterns are also important.

Sediment budgets are also a key driver of landform development. For example, sand dunes and dunefields will only accumulate in areas where the amount of sand being blown to a location by the wind is greater than the amount of sediment being blown away from the location. As highlighted in Table 3, some specific types of sand dunes will form where the sediment supply is low (e.g. barchans) and others will only form where sediment supply is high (e.g. star dunes). The accumulated sediment is stored within the dune. Similarly, alluvial fans store sediment at the interface between upland areas and lowland areas.

The **magnitude and frequency** of sediment transporting events is important in shaping dryland landscapes. There are substantial river systems in deserts that have no permanent water, but occasional high-magnitude flood events may occur from time to time. These are referred to as high magnitude/low frequency events. For example, the sand dunes at the northern (downwind) margin of the Namib sand sea are estimated to be advancing in to the Kuiseb Canyon at a rate of approximately 2 m yr^{-1}. However the dunes do not advance all the way across the canyon because every few years a flood of sufficient magnitude to erode the dune advance occurs.

C. Approaches to studying drylands

It may be difficult for students to directly experience dryland landscapes within the course of their A Level studies.

At the UK coast insights in to the relationship between sand transport by wind and the development of dunes using simple anemometers to measure wind speed and sand traps made from twinwall greenhouse polycarbonate.

Google Earth is an excellent tool for exploring dryland landscapes. Different sand dune types can be clearly differentiated (Figure 4), as can the range of different dryland fluvial landscapes.

a) b) c)

Figure 5: *Images from Google Earth of a) barchans dunes in the southern Namib desert, b) linear dunes in the southwest Kalahari and c) star dunes in the Grand Erg Oriental, North Africa © Google Earth*

It is also possible to use the historical imagery in Google Earth to look at rates of landscape change. A good example is the migration of the sand dune that famously threatened the location where the first Star Wars film was made (Figure 5).

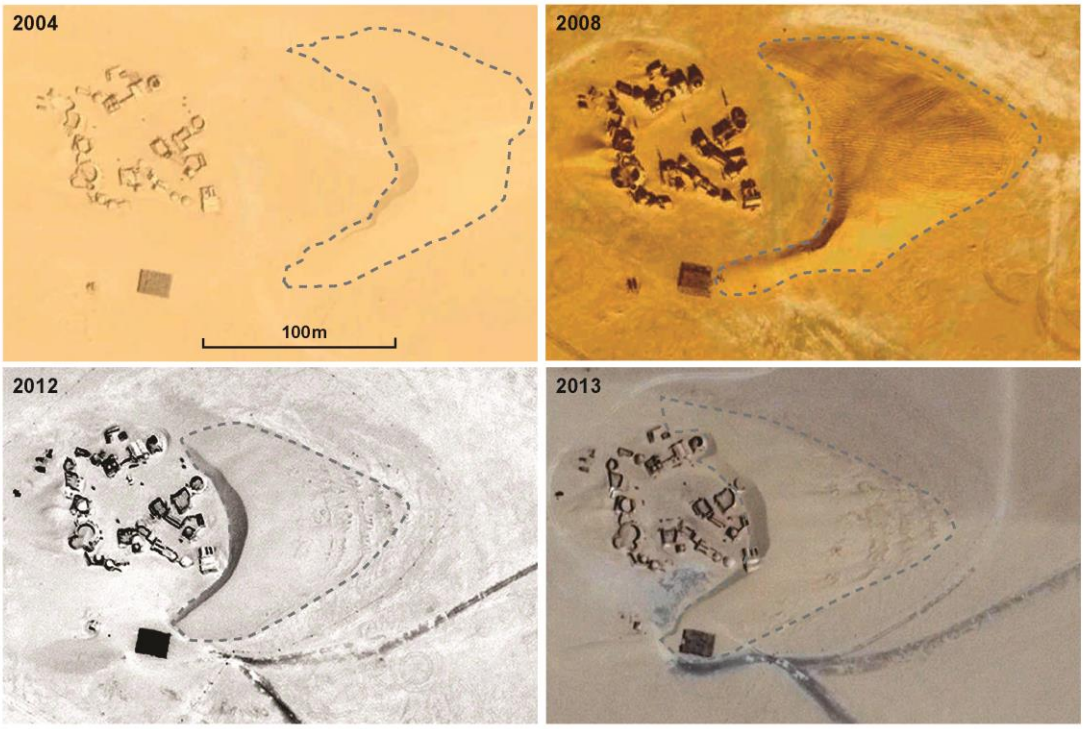

Figure 6: *Google Earth images showing a barchan sand dune (dashed outline) migrating from east to west at a rate of up to 15 m per year and threatening to engulf the film set city of Mos Espa, from Star Wars Episode 1: The Phantom Menace © Google Earth*

YouTube is also a useful online resource particularly for illustrating fluvial processes in dryland landscapes. There is good footage of sudden flood events inundating previously dry river beds from several locations including the Kuiseb Canyon in Namibia, as mentioned above (type 'Kuiseb flood' in to the search box) and Morocco (type 'Kuiseb flood' in to the search box). These videos illustrate well the speed at which the flood can occur and also the amount of sediment and debris that they can transport.

4. Relevant case studies.

The Namib Desert, southern Africa – this dryland landscape extends from the west coast of southern Africa 120-200 km inland. It includes the 34,000 km^2 Namib Sand Sea which contains excellent examples of all the main dune types. There are classic canyon landscapes in the south of the desert e.g. Fish River Canyon.

The Sahara Desert, North Africa – occupying around one-third of the African continent, the Sahara includes a wide diversity of dryland landscapes and is also the world's largest dust source.

Australia – after Antarctica, Australia is Earth's driest continent although it does not experience hyper-aridity. Australia is tectonically very stable and low-lying and the interior landscape is dominated by sand dunes (40% of dryland region). Pans, or dry lakes, are also very common.

Antarctica – 98% of Antarctica is ice-covered and the ice-free areas of land are hyper-arid receiving only 3-50 mm rainfall equivalent per year. The largest ice-free area is the McMurdo Dry Valleys which contain sand dunes and dry lake beds and are also a local source of dust.

SW USA – the North American deserts include the southwest USA and parts of northern Mexico. Tectonic activity exerts a major control on the landscape which includes the Basin and Range series of block-faulted north to south trending mountain ranges and basins (including Death Valley), and the Colorado Plateau, a high or cold desert with extensive mesa and scarp landscapes and canyons.

5. Resources

RGS-IBG Resources

Arid environments - Life on the Margins: Natural Hazards in the Gobi Desert**:**
http://www.rgs.org/OurWork/Schools/Teaching+resources/Key+Stage+5+resources/Key+Stage+5+-+From+the+field+resources/Arid+environments/Arid+environments.htm

60 second guide: Hot Desert Biome: http://www.rgs.org/NR/rdonlyres/615FC853-D6A1-49AB-99A5-138BE4663AE0/0/60sHotDesertBiome.pdf

60 second guide: Cold Desert Biome: http://www.rgs.org/NR/rdonlyres/DF3E3A9C-C022-4A25-A070-F904961D2126/0/60sColdDesertBiome.pdf

Academic textbooks

Goudie, A.S. 2002. Great Warm Deserts of the World. Oxford University Press.

Thomas, D.S.G. 2011. Arid Zone Geomorphology 3rd edition. Wiley-Blackwell, Oxford.

Online Resources

Namib Sand Sea Digital Database - https://www.shef.ac.uk/sandsea/data
Focusing on the Namib dunefield, this is a compilation of data layers including wind data, a map of dune types, satellite images and vegetation cover. All data layers are available as .kml files for direct visualisation in Google Earth.

DustWatch Australia - http://www.dustwatch.edu.au
This is a collaborative effort to monitor and map wind erosion in Australia. Click on the location of different monitoring stations to see how the seasonal timing of dust storms varies across the country. Also includes annual maps of dust storm frequency and information about weather and climate.

Google Earth
Landforms in drylands are often very clearly defined on aerial photographs and satellite images such as those in Google Earth and other similar resources due to the lack of vegetation.

YouTube
A large number of crowd-sourced videos of flood events, dust storms and even dune migration can be found on YouTube. Some are accompanied by commentary or text explanation.