

# About Drought

Maximising the impact of UK research on drought & water scarcity



Photo: Emma Shepherd

## Wetlands Report Card 2020

This publication covers the impacts of drought and water scarcity on wetlands and covers impacts, the ecosystem response, future scenarios and mitigation.

It has been produced by About Drought, the UK's Drought & Water Scarcity Research Programme, which consists of 5 integrated research projects, funded by the UK research councils.

It is designed to be used by all, including the general public.

It is one of a series of report cards summarising current and future aspects of water scarcity in the main ecosystems of the UK.

Prepared by: Mike Acreman<sup>1,2</sup>, Anne Jo Dobel<sup>3</sup> & François Edwards<sup>4</sup>

<sup>1</sup>UKCEH Research Fellow

<sup>2</sup>Director, Hydro\_Ecology Consulting Ltd

<sup>3</sup>UKCEH Edinburgh

<sup>4</sup>UKCEH Wallingford

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## Wetlands in the UK

Wetlands form fundamental parts of the UK's landscape, embracing a diverse range of habitats including fens, bogs, marshes, peatlands, wet grasslands, wet woodlands and floodplains. Wildlife support is a particularly important aspect of UK wetlands. Over 3,500 species of invertebrates, 150 species of aquatic plant, 22 species of duck and 33 species of wader, have been identified living in UK wetlands, whilst all six of our native amphibian species depend on wetlands for breeding (Merritt, 1994). Wetlands occupy the transitional zones from permanently wet to generally drier areas. They share characteristics of both environments, yet cannot be classified unambiguously as either aquatic or terrestrial. It is the presence of water for some significant period of time that creates the soils, its micro-organisms, and the plant and animal communities such that, the land functions in a different way from either fully aquatic or dry habitats (Acreman & Jose, 2000). Hydrology is probably the single most important determinant for the establishment and maintenance of specific types of wetlands and wetland processes. Furthermore, when hydrological conditions in wetlands change even slightly, the biota may respond with massive changes in species abundance and richness, and ecosystem productivity (Mitsch & Gosselink, 1993). Drought conditions will alter wetland processes and the species dependent on them.

Wetlands have evolved and adapted to natural fluctuations in

the hydrological cycle including droughts, floods and 'normal' conditions. Although wetland ecosystems may change during droughts, these should be seen as natural disturbances (Brock et al., 2003) rather than adverse impacts. Wetlands normally recover to pre-drought conditions when re-wetted. Disturbance history plays a major role in determining the type and form of freshwater biological communities (Cattanéo et al., 2001). For example, under constant wet conditions, the productivity of wetlands gradually declines and plant communities shift from annual species that produce an abundance of seeds to perennials, such as bulrush (typha), reducing habitat quality for waterfowl and other wildlife.



Photo: Karen Arnold from Pixabay

Wetlands occupy the transitional zones from permanently wet to generally drier areas. They share characteristics of both environments yet cannot be classified unambiguously as either aquatic or terrestrial.



## Drought in Wetlands

During droughts, wetlands dry-out and bottom sediments are exposed to air stimulating decomposition, releasing nutrients and allowing annual seeds to germinate, thus stimulating productivity (Brakhage, 2018). Some wetland species may rely on periodic drought conditions for part of their life histories, or have life strategies suited to exploiting the habitat or changed environmental conditions that are created by droughts (Gordon et al. 1992). Thus conservation of biological and genetic diversity in freshwater ecosystems is best served by protecting natural hydrological variability (Horne et al., 2017), including droughts (Everard, 1996).

Mankind's influences during the anthropocene have altered the natural environment and it is likely that human-induced changes will continue to increase (Convention on Biological Diversity, 2014). Abstraction of water has intensified droughts, increasing disturbance. Climate change has or will make droughts more frequent, reducing recovery time. Habitat loss has isolated wetlands, hampering re-colonisation after droughts. Consequently, droughts may be more likely to result in long term or permanent changes in wetland ecosystems in the future.

In this scorecard we focus on the response of freshwater wetlands to direct alterations in wetness during droughts, due normally to reduced rainfall, river flow and groundwater discharge, and increased evaporation, plus indirect pressures such as abstraction of water.



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# Mitigating Actions - Physical

## Physical effects of drought & mitigating actions

Effects	Response	Future scenarios	Mitigation
<p>The physical responses of wetlands to droughts are generated, mainly, by lower levels of rainfall and higher air temperatures. Lower levels of rainfall impact both directly on wetlands and on surrounding catchments reducing runoff. Higher air temperatures are usually associated with lower levels of atmospheric humidity, leading to increased evaporation rates over the surface of the waterbody and greater transpiration from wetland plants.</p>	<p>During droughts, wetland surface water bodies, such as ponds, contract in area and volume, with rates depending on their morphology. Larger areas of open water become fragmented as they divide into small separate pools. Areas periodically inundated, such as floodplains, may remain dry for longer periods than normal. Soils usually saturated start to dry-out and crack.</p> <p>Groundwater levels fall during droughts and wetlands may switch from being supplied by aquifers to becoming a supplier as water infiltrates into aquifers. During droughts, surface outflow may cease from peatlands (Burke, 1968; Newson, 1981; Boeye &amp; Verheyen, 1992). Because of the water storage effects in the landscape, river-fed wetland ecosystems are more resilient to drought than rain-fed wetlands (Acreman &amp; Blake, 2016). By the same token, groundwater-fed wetlands are generally the most resilient in less severe droughts. Wetlands normally revert to their pre-drought physical state once re-wetted, but this may take time (Large et al., 2007), in some cases several years (Hudson, 1988). In extreme droughts, changes in soil structure may be irreversible in the short term and may mean that pre-drought soil-water storage capacities will never be regained (Hudson, 1988).</p>	<p>Reduced summer rainfall and increased summer evaporation predicted for Great Britain by 2050 will put stress on wetlands in late summer and autumn with greater impacts in the south and east of GB than in the north and west. In addition, impacts on rain-fed wetlands will be greater than on those dominated by river inflows. (Acreman et al., 2009).</p>	<p><b>MI</b> Many managed wetlands, incorporate large water features that not only provide habitat but act as reservoirs during dry periods.</p> <p>Drainage of blanket peats has been shown to increase dry period flow to streams (Burke, 1975; Robinson et al., 1991) due to lower evaporation. Drain-blocking can result in higher and more stable water tables within peat wetlands, making them better able to resist drought periods (Wilson et al., 2011).</p>

# Mitigating Actions - Chemical

## Chemical effects of drought & mitigating actions

Effects	Response	Future scenarios	Mitigation
<p>As water depth and volume decline in wetlands during droughts and temperatures rise, so their chemistry changes including dissolved oxygen level, salinity, dissolved organic carbon, turbidity and nutrient levels, especially nitrogen and phosphorus (Lake, 2011).</p>	<p>Drought in wetlands results in increased peat temperature, lower dissolved oxygen and higher pH leading to greater oxidation of sulphur compounds (Freeman et al., 1993) and lower concentrations of nitrate and ammonium (Proctor, 2006) and iron (Hughes et al., 1997). Short-term droughts do not affect the acid neutralizing capacity or nutrient availability in fens (Cusell et al., 2015). Dissolved organic carbon can decrease due to drought-induced acidification (Scott et al., 1998; Worrall et al., 2006; Clark et al., 2012), but increases again after droughts (Grand-Clement et al., 2014).</p> <p>Peat wetlands become CO<sub>2</sub> sources during drying (Estop-Aragnes et al., 2016), which can stimulate microbial growth that causes the breakdown of organic matter (Fenner &amp; Freeman, 2011). In contrast, CH<sub>4</sub> production is lower under drought conditions (Freeman et al., 2002), which persists at least one month beyond the end of the drought.</p> <p>During extreme droughts, nitrous oxide (N<sub>2</sub>O) emissions (which can deplete stratospheric ozone) can increase exponentially (Dowrick et al., 1999) and the enzyme B-glucosidase can stimulate increases in the concentration of magnesium and calcium (Freeman et al., 1997).</p> <p>Re-wetting of the peat after significant water table draw-down can produce elevated arsenic concentrations in receiving waters (Rothwell et al., 2009).</p>	<p>Reduced summer rainfall and increased summer evaporation predicted for Great Britain by 2050 will increase the likelihood of droughts in late summer and autumn, with greater impacts in the south and east of GB than in the north and west (Acreman et al., 2009). Thus chemical changes associated with droughts will be more likely and more intense.</p>	<p><b>M2</b> Many managed wetlands, incorporate large water features that not only provide habitat but act as reservoirs during dry periods.</p> <p>Drainage of blanket peats has been shown to increase dry period flow to streams (Burke, 1975; Robinson et al., 1991) increasing dilution in receiving waters. Drain-blocking can result in higher and more stable water tables within peat wetlands, which can reduce chemical changes within the wetland (Wilson et al., 2011).</p>

# Mitigating Actions - Biological

## Biological effects of drought & mitigating actions

Effects	Response	Future scenarios	Mitigation
<p>Algae, macrophytes, invertebrates, fish and aquatic birds have variable spatial and temporal responses to abiotic changes that occur during droughts, depending on species resistance and resilience, competitive and predatory interactions, and the timing and characteristics of the drought.</p> <p>Whereas some species may have life strategies suited to exploiting the habitat or changed environmental conditions that are created by drought, for other organisms it is a time of stress (Gordon <i>et al.</i>, 1992).</p>	<p>Biological tolerance and response to drought depends on the unique characteristics and adaptations of species. During droughts wetlands dry-out and bottom sediments are exposed to air, stimulating decomposition, releasing nutrients and allowing annual seeds to germinate, thus stimulating productivity (Brakhage, 2018). The toiche zone, normally inundated but exposed during low-water conditions, is subject to waves of colonisation and subsequent extinction variously by terrestrial and aquatic macrophyte species (Palmer &amp; Newbold, 1983).</p> <p>Droughts can be accompanied by the disappearance of characteristic black alder carr species and a dominant growth of more drought-resistant species such as <i>Rubus idaeus</i> L. and <i>Rubus fruticosus</i> L. (Stortelder <i>et al.</i>, 1998). The number of wading birds successfully breeding often declines and chick mortality is higher (Burston, 2006). Droughts may prevent invasive species from becoming established. Permanent wetlands may lose macroinvertebrate fauna during droughts but can acquire fauna typical of temporary ponds (Jeffries, 1994), which are more resilient to drought (Biggs <i>et al.</i>, 1994). Drying-out of temporary wetlands does not diminish their conservation value, species richness or the likely occurrence of rare species (Collinson <i>et al.</i>, 1995).</p> <p>Some wetland species rely on periodic drought conditions for part of their life histories or have life strategies suited to exploiting the habitat or changed environmental conditions that are created by drought (Gordon <i>et al.</i> 1992). Amphibians benefit from droughts as the following year is safer for their tadpoles (Hawkins, 1995) because their predators, such as fish, are reduced or eliminated (Oldham, 1996). The rhizosphere beneath <i>Calluna</i> is disproportionately affected by drought conditions due to its concentration of root growth in the upper layers of the peat, rather than the deeper roots of <i>Juncus</i> which are more resilient (Genney <i>et al.</i>, 2000). Droughts can bring shifts in dominant species (Breeuwer <i>et al.</i>, 2009), such as <i>Sphagnum</i> species.</p>	<p>Predicted reduced summer rainfall and increased summer evaporation will put stress on wetland plant communities in late summer and autumn, with greater impacts in the south and east of GB than in the north and west (Acreman <i>et al.</i>, 2009). It may not be possible to conserve some wetland species that are already on the margin of their ranges.</p>	<p><b>M3</b> Management of water abstractions during drought is important. Abstraction from aquifers feeding wetlands can threaten their biodiversity (Fojt, 1994). Increased groundwater abstraction during droughts has led to the conversion of <i>Schoeno-Junceta</i> communities into degraded types of <i>Cirsio-Molinietum</i>, <i>Juncus subnodulosus</i> fen meadow (Harding, 1993). Proximity and connectivity between wetlands is also key. Recovery after drought depends on the ability of organisms that are lost to recolonise. Isolated populations of rare heath reptiles including rare species, such as the smooth snake and sand lizard may be totally lost during droughts, with little chance of natural recolonization (Burston, 2006). Managing the land to reduce habitat fragmentation may reduce this risk (Lawton <i>et al.</i>, 2010).</p>

# Mitigating Actions - Societal

## Societal effects of drought & mitigating actions

Effects	Response	Future scenarios	Mitigation
<p>Wetlands provide a wide range of ecosystem services to people, including management of floods, reduction in water pollutants, storage of carbon, recreation, and a sense of well-being and social history (Maltby, 1986). Such services will change as the character of the wetland changes (Maltby &amp; Acreman, 2011). Whilst ecosystem condition during and after droughts can be assessed objectively from physical, chemical and biological data, assessment of ecosystem services requires knowledge of preferences of the service user in the form of aesthetic, social or economic data. This may be inconsistent between users. For example, one person may perceive a dried-up wetland during a drought as negative, another person may view it positively</p>	<p>Under moist conditions peat soils are hydrophilic and can absorb water during rainfall (if they are not already saturated), which can reduce flooding downstream (Bullock &amp; Acreman, 2003). However, when dry peat soils become hydrophobic and repel water (Rezanezhad <i>et al.</i>, 2007), meaning that rainfall moves rapidly to watercourses via overland flows (Goulsbra &amp; Evans, 2011), this can increase flooding downstream. Reduced soil water storage capacity of peat soils after drought (Hudson, 1988) may diminish any flood reduction capacity of wetlands for many months, years or permanently.</p> <p>During droughts, reduced water volumes in wetlands, or in streams receiving water from wetlands, will diminish water resources (Newson, 1981; Burt, 1995) because evapotranspiration depletes surface outflow (Gilvear <i>et al.</i>, 1993).</p> <p>Groundwater from upland peaty soil aquifers can provide baseflow during dry periods that dilute pollutant inputs from lowland areas at the large catchment scale (Capell <i>et al.</i>, 2011) improving water quality. During droughts dissolved organic carbon (DOC) decreases (Worrall <i>et al.</i>, 2006; Clark <i>et al.</i>, 2012) but during subsequent rainfall events, following intense dryness, DOC (Grand-Clement, 2014) and arsenic (Rothwell <i>et al.</i>, 2009) increases. During dry periods release of methane from peat soils in wetlands usually reduces, but emission of carbon dioxide tends to increase as the soil oxidises (Acreman <i>et al.</i>, 2011), thus altering greenhouse gas fluxes to the atmosphere.</p> <p>Wetlands provide grazing for cattle and, in response, this grazing maintains certain wetland types, such as wet grasslands (Crofts &amp; Jefferson, 1999). During droughts, loss or decline of wetland species will reduce grazing opportunity for cattle.</p> <p>Changes in appearance of wetlands during droughts and loss of species, such as birds and reptiles, will alter the social values of wetlands, including landscape aesthetics, recreation and cultural associations. Drying of wetland soils during droughts may lead to degradation or loss of archaeological remains or scientifically important pollen sequences (Skinner <i>et al.</i>, 2014).</p>	<p>Future increase in drought frequency in many areas across Europe, due to global climate changes, are likely to threaten the persistence of wetland ecosystems services, such as biomass production, nutrient removal, carbon storage and fish production (Okruszko <i>et al.</i>, 2011).</p>	<p><b>M4</b> Drainage of blanket peats has been shown to increase dry period flow to streams (Burke, 1975; Robinson <i>et al.</i>, 1991) due to lower evaporation. This could increase water resources in receiving streams. However, drain-blocking can result in higher and more stable water tables within wetlands themselves, reducing disturbance during drought periods (Wilson <i>et al.</i>, 2011).</p>



# References

- Acreman, M.C., & José, P. 2000 Wetlands. In: Acreman, M.C. (Ed) *The Hydrology of the UK – a study of change*. Routledge, London; Acreman, M.C., Booker, D.J. & Riddington, R. 2003 Hydrological impacts of floodplain restoration: a case study of the river Cherwell, UK. *Hydrology and Earth System Sciences*. 7,1, 75-86
- Acreman, M.C., Blake, J.R., Booker, D.J., Harding, R.J., Reynard, N., Mountford, J.O., Stratford, C.J. 2009 A simple framework for evaluating regional wetland ecohydrological response to climate change with case studies from Great Britain. *Ecohydrology* 2, 1-17.
- Acreman, M.C., Harding, R.J., Lloyd, C., McNamara, N.P., Mountford, J.O., Mould, D.J., Purse, B.V., Heard, M.S., Stratford & C.J., Dury, S. 2011 Trade-off in ecosystem services of the Somerset Levels and Moors wetlands *Hydrological Sciences Journal*. 56, 8, 1543-1565.
- Acreman, M.C. & Blake, J.R. 2016 Project eco-hydrological response of wetlands in England and Wales to likely future alterations in drought. Report to NERC Marius Drought project. Centre for Ecology & Hydrology.
- Biggs, J., Corfield, A., Walker, D., Whitfield, M. & Williams, P. J. 1994. New approaches to the management of ponds. *British Wildlife*, 5, 273-287. Best, J. 2019 Anthropogenic stresses on the world's big rivers. *Nature Geoscience* doi: 10.1038/s41561-018-0262-x
- Boeye, D. & Verheyen, R.F. 1992 The hydrological balance of a groundwater discharge fen *Journal of Hydrology* 137 (s 1-4), 149-163 DOI: 10.1016/0022-1694(92)90053-X Brakhage, D. 2018 The positive effects of drought. Ducks Unlimited <https://www.ducks.org/conservation/national/the-positive-effects-of-drought>
- Brakhage, D. 2018 The positive effects of drought. Ducks Unlimited <https://www.ducks.org/conservation/national/the-positive-effects-of-drought>
- Breuer, A., Robroek, B.J.M., Limpens, J., Heijmans, M.M.P.D., Schouten, M.G.C. & Berendse, F. 2009 Decreased summer watertable depth affects peatland vegetation *Basic and Applied Ecology* 10 330-339
- Brock, M. A., Nielsen, D.L., Shiel, R.J., Green, J.D. & Langley, J.D. 2003 Drought and aquatic community resilience: the role of eggs and seeds in sediments of temporary wetlands. *Freshwater Biology*, 48, 7, 1207-1218 doi.org/10.1046/j.1365-2427.2003.01083.x
- Bullock A. & Acreman, M.C. 2003 The role of wetlands in the hydrological cycle. *Hydrology and Earth System Sciences*. 7,3, 75-86.
- Burke, W., 1968. Drainage of blanket peat at Glenamoy. *Proc. 2nd International Peat Congress*. HMSO, Edinburgh, UK. 809-817.
- Burke, W., 1975. Aspects of the hydrology of blanket peat in Ireland. *Hydrology of marsh-ridden areas*, Proc. of the Minsk Symp. (June, 1972), International Association of Hydrological Sciences, UNESCO/IAHS, Paris. 171-182
- Burston, P. 2006 DRY ROT: is England's countryside dying of thirst? The Impacts of droughts and water shortages on England's Wildlife RSPB [www.rspb.org.uk/waterwetlands](http://www.rspb.org.uk/waterwetlands) Burt, T. P. 1995. The role of wetlands in runoff generation from headwater catchments. In: *Hydrology and hydrochemistry of British wetlands*, J. Hughes and L. Heathwaite (Eds.) Wiley, Chichester, UK. 21-38
- Burt, T. P. 1995. The role of wetlands in runoff generation from headwater catchments. In: *Hydrology and hydrochemistry of British wetlands*, J. Hughes and L. Heathwaite (Eds.) Wiley, Chichester, UK. 21-38
- Capell, R., Tetzlaff, D., Malcolm, I.A., Hartley, A.J. & Soulsby, C. 2011 Using hydrochemical tracers to conceptualise hydrological function in a larger scale catchment draining contrasting geologic provinces *Journal of Hydrology* 408, 164-177
- Cattanéo, F., Carrel, G., Lamouroux, N. & Breil, P. 2001 Relationships between hydrology and cyprinid reproductive success in the lower Rhône at Montélimar. *Archiv für Hydrobiologie*, 151, 3, 427-450.
- Clark J. M., Heinemeyer, A., Martin, P. & Bottrell, S. H. 2012. Processes controlling DOC in pore water during simulated drought cycles in six different UK peats *Biogeochemistry* 109, 253-270 DOI 10.1007/s10533-011-9624-9
- Collinson, N. H., Biggs, J., Corfield, A., Hodson, M. J., Walker, D., Whitfield, M. & Williams, P. J. 1995. Temporary and permanent ponds: an assessment of the effects of drying out on the conservation value of aquatic macroinvertebrate communities. *Biological Conservation*, 74, 125-133.
- Convention on Biological Diversity 2014 *Global Biodiversity Outlook 4*. CBD Montréal, 155 pp
- Crofts, A. & Jefferson, R.G. (eds.) 1999. *The Lowland Grassland Management Handbook*. Second edition. <http://publications.naturalengland.org.uk/publication/35034>.
- Cusell, C., Mettrop, I.S., van Loon, E.E., Lamers, L.P.M., Vorenhout, M. & Kooijman, A.M. 2015 Impacts of short-term droughts and inundations in species-rich fens *Ecological Engineering* 77, 127-138
- Dowrick, D.J., Hughes, S., Freeman, C., Lock, M.A., Reynolds, B. & Hudson, J.A. 1999 Nitrous oxide emissions from a gully mire in mid-Wales, UK, under simulated summer drought *Biogeochemistry* 44: 151-162 Environment Agency 2017 Drought response: our framework for England. Environment Agency, Bristol. 33 pp
- Estop-Aragónés, C., Zaja, K. & Blodau, C. 2016 Effects of extreme experimental drought and rewetting on CO<sub>2</sub> and CH<sub>4</sub> exchange in mesocosms of 14 European peatlands with different nitrogen and sulfur deposition *Global Change Biology*, 22, 2285-2300, doi: 10.1111/gcb.13228
- Everard, M. 1996 The importance of periodic droughts for maintaining diversity in the freshwater environment. Proceedings of the FBA Annual Scientific Meeting on "Life at the Extremes", held at the Linnean Society, London, in July 1996.) [https://www.researchgate.net/publication/265081812\\_The\\_importance\\_of\\_periodic\\_droughts\\_for\\_maintaining\\_diversity\\_in\\_the\\_freshwater\\_environment](https://www.researchgate.net/publication/265081812_The_importance_of_periodic_droughts_for_maintaining_diversity_in_the_freshwater_environment)
- Fenner, N. & Freeman, C. 2011 Drought-induced carbon loss in peatlands *Nature Geoscience*, November 2011 DOI: 10.1038/NGEO1323
- Fojt, W.J. 1994. Dehydration and the threat to East Anglian fens, England. *Biological Conservation* 69, 163-175
- Freeman, C., Hudson, J., Lock, M.A. & Reynolds, B. 1993. A field-based approach to investigating potential impacts of drought induced by climatic change upon wetlands *Extreme Hydrological Events: Precipitation, Floods and Droughts*. Proceedings of the Yokohama Symposium, July 1993. IAHS Publication 213.
- Freeman, C., Liska, G., Ostle, N.J., Lock, M.A., Hughes, S., Reynolds, B. & Hudson, J. 1997. Enzymes and biogeochemical cycling in wetlands during a simulated drought *Biogeochemistry* 39, 2, 177-187
- Genney, D.R., Alexander, I.J. & Hartley, S.E. 2000. Exclusion of grass roots from soil organic layers by Calluna: the role of ericoid mycorrhizas. *Journal of Experimental Botany*, 51, 347, 1117-1125
- Gilvear D.J., Andrews R., Tellam J.H., Lloyd J.W. & Lerner D.N. 1993. Quantification of the water balance and hydrogeological processes in the vicinity of a small groundwater-fed wetland, East Anglia, U.K.. *Journal of Hydrology*, 144, 311-334.
- Gordon, N. D., McMahon, T. A. & Finlayson, B. L. 1992. *Stream Hydrology: An Introduction for Ecologists*. John Wiley and Sons, Chichester. 526 pp.
- Goulsbra, C.S. & Evans, M. 2011. Evidence of the occurrence of infiltration excess overland flow in an eroded peatland catchment and implications for connectivity in a changing climate. *Geophysical Research Abstracts*, 13. EGU General Assembly 2011.
- Grand-Clement, E., Luscombe, D.J., Anderson, K., Gatis, N., Benaud, P. & Brazier, R.E. 2014 Antecedent conditions control carbon loss and downstream water quality from shallow, damaged peatlands. *Science of the Total Environment* 493, 961-973
- Harding, M. 1993. Redgrave and Lopham Fens, East Anglia, England: a case study of change in flora and fauna due to groundwater abstraction. *Biological Conservation*, 66, 35-45.
- Hawkins, J. 1995. Ponds left high and dry - with wildlife left living on the edge. *Farming Conservation*, April 1995, 18-20.
- Horne, A., Webb, J.A., Stewardson, M., Richter, B., M. & Acreman, M.C (eds) 2017. *Water for the environment; from policy and science to implementation and management*. Elsevier
- Hudson, J. A. 1988. The contribution of soil moisture storage to the water balances of upland forested and grassland catchments, *Hydrological Sciences Journal*, 33:3, 289-309. DOI: 10.1080/02626668809491249



# References

- Hughes, S., Reynolds, B., Hudson, J.A. & Freeman, C. 1997. Effects of summer drought on peat soil solution chemistry in an acid mire. *Hydrology & Earth System Sciences*, 1, 3, 661-669.
- Jeffries, M.J. 1994. Invertebrate communities and turnover in wetland ponds affected by drought *Freshwater Biology*, 32, 603-612
- Lake, P.S. 2011. Drought and aquatic ecosystems: effects and responses. Wiley-Blackwell. pp 381.
- Large, A.R.G., Mayes, W.M., Newson, M.D. & Parkin, G. 2007. Using long-term monitoring of fen hydrology and vegetation to underpin wetland restoration strategies *Applied Vegetation Science* 10, 417-428.
- Lawton, J.H., Brotherton, P.N.M., Brown, V.K., Elphick, C., Fitter, A.H., Forshaw, J., Haddow, R.W., Hilborne, S., Leafe, R.N., Mace, G.M., Southgate, M.P., Sutherland, W.J., Tew, T.E., Varley, J., & Wynne, G.R. 2010. Making Space for Nature: a review of England's wildlife sites and ecological network. Report to Defra.
- Maltby, E. 1986. Waterlogged wealth. Earthscan.
- Maltby, E. and Acreman, M.C. 2011. Ecosystem Services of Wetlands: pathfinder for a new paradigm. *Hydrological Sciences Journal*. 56, 8 1-19.
- Merritt, A. 1994. Wetlands, Industry and wildlife -- a manual of principles and practices. The Wildfowl and Wetland Trust, Slimbridge.
- Mitsch, W.J. & Gosselink, J. G. 1993. Wetlands (2<sup>nd</sup> ed.). Van Nostrand Reinhold Company. 720 pp.
- Mitsch, W. J. and Gosselink, J. G. 1993 Wetlands. Van Nostrand Reinhold, New York. Second Edition
- Newson, M.D. 1981. Mountain streams. In: Lewin, J. (Ed) *British Rivers*. George Allen & Unwin 59-89
- Okruszko, T., Duel, H., Acreman, M., Grygoruk, M., Florke, M. & Schneider, C. 2011. Broad-scale ecosystem services of European wetlands-overview of the current situation and future perspectives under different climate and water management scenarios. *Hydrological Sciences Journal*, 56,1501–1517.
- Oldham, R. S. 1996. Floodplain as amphibian habitat. In: Bailey, R. Hose, P. & Sherwood, B. *Proceedings of the Symposium of United Kingdom Floodplains*. Samara Publishing Ltd, Cardigan.
- Palmer, M. & Newbold, C. 1983. Wetland and riparian plants in Great Britain. Focus on Nature Conservation, 1, Nature Conservancy Council, London.
- Proctor, M.C.F. 2006. Temporal variation in the surface-water chemistry of a blanket bog on Dartmoor, southwest England: analysis of 5 years' data. *European Journal of Soil Science*, 57, 167–178
- Rezanezhad, F., Price, J.S., Quinton, W.L., Lennartz, B., Milojevic, T. & van Cappellen, P. 2007. Structure of peat soils and implications for water storage, flow and solute transport: A review update for geochemists. *Journal of Hydrology*, 337, 315– 325
- Robinson, M., Gannon, B. & Schuch, M. 1991. A comparison of the hydrology of moorland under natural conditions, agricultural use and forestry *Hydrological Sciences Journal*, 36, 6, 565-577.
- Rothwell, J.J., Taylor, K.G., Ander, E.L., Evans, M.G., Daniels, S.M., & Allott, T.E.H. 2009. Arsenic retention and release in ombrotrophic peatlands. *Science of the Total Environment* 407, 1405–1417.
- Scott, M.J., Jones, M.N., Woof, C. & Tipping, E. 1998. Concentrations and fluxes of dissolved organic carbon in drainage water from an upland peat system. *Environment International*, 24, 5/6, 537-546
- Skinner, A., Orr, H.G., Acreman, M.C. & Blake, J.R. 2014. The Wetland Tool – Adapting wetlands to deal with future climate change *Bulletin of the Chartered Institute of Ecology and Environmental Management*, 85, 20-24
- Stortelder, A.H.F., Hommel, P.V.F.M., de Waal, R.W., van Dort, K.W., Vrieling, J.G. & Wolf, R.J.A.M. 1998. Broekbossen, bosccosystemen van Nederland I. KNNV, Utrecht, 34p.
- Wilson, L., Wilson, J., Holden, J., Johnstone, I., Armstrong, A. & Morris, M. 2011. The impact of drain blocking on an upland blanket bog during storm and drought events, and the importance of sampling-scale *Journal of Hydrology*, 404, 198–208.
- Worrall, F., Burt, T.P. & Adamson, J. 2006. Do nitrogen inputs stimulate dissolved organic carbon production in upland peat bogs? *Global Biogeochemical Cycles*, 20, GB3013, doi: 10.1029/2005GB002524.

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Maximising the impact of UK research on drought & water scarcity



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