Institution: University College London		
Unit of Assessment: 14 – Geography and Environmental Studies		
Title of case study: Improving water and food security in tropical Africa		
Period when the underpinning research was undertaken: 2000 - 2020		
Details of staff conducting the underpinning research from the submitting unit:		
Name:	**Role:**	**Period employed by submitting HEI:**
Richard Taylor	Professor of Hydrogeology	2000-present
Mohammad Shamsudduha	Postdoctoral Fellow	2012-2019
Mark Cuthbert	Postdoctoral Fellow	2016-2017
Period when the claimed impact occurred: 2013-2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact (indicative maximum 100 words)

Dependence upon groundwater to alleviate poverty in countries in tropical Africa is substantial and growing yet the sustainability of groundwater withdrawals under climate change has remained unclear. Taylor's research in nine countries across tropical Africa shows groundwater to be naturally resilient to climate change as the intensification of rainfall brought about by global warming often serves to enhance groundwater replenishment. His research provides a robust, evidence-led platform to develop climate-resilient strategies across tropical Africa to sustain the expansion of irrigated agriculture and improve access to safe water in pursuit of UN Sustainable Development Goals (SDGs) 2 (zero hunger) and 6 (universal access to safe water and sanitation). Governments are employing Taylor's research to improve access to safe water in rural and urban Uganda, to sustain the water supply to Tanzania's rapidly growing dryland capital city (Dodoma), and to expand small-scale irrigation and access to safe water in rural Niger.

2. Underpinning research (indicative maximum 500 words)

Sustainable access to adequate quantities of freshwater is one of the most critical challenges humans face in the 21st century. Rapid population growth and rising living standards are increasing freshwater withdrawals in low- and middle-income countries across the tropics while climate change amplifies variability and uncertainty in freshwater available from rivers and lakes. Conventional approaches addressing intermittent or sustained water scarcity have typically involved the construction of dams that incur exorbitant capital costs, intensify water losses in a warming world, and exacerbate conflict between upstream and downstream users. The importance of identifying climate-resilient development pathways to the realisation of the UN SDGs 2 and 6 cannot be overstated.

Since 2000, Taylor's research combining in-depth empirical observations through field study with evidence from remote sensing and models has made fundamental contributions to the understanding of groundwater systems in tropical Africa. Early work by Taylor **[R1/R2]** traced the origin of tropical groundwater to heavy rainfall and identified productive groundwater-bearing formations through the long-term evolution of the landscape. The latter finding informed quantitative mapping of groundwater across Africa by Taylor with the British Geological Survey that revealed, for the first time, the volume of African groundwater resources (~660,000 km^3), which for many countries is ten to hundred times their annual volume of river discharge. This research also provided a methodology for mapping groundwater at national and regional scales to inform and improve assessments of water security.

To evaluate the renewability of quantified groundwater storage, Taylor broadened his analyses of groundwater recharge in humid environments **[R1]** to semi-arid Tanzania **[R3]** and then across tropical Africa **[R4/R5/R6]** through the *GroFutures* [i] and *AfriWatSan* [iv] projects that he leads. Taylor first worked closely with the Government of Tanzania to compile the longest record of groundwater levels ever assembled in tropical Africa, which, combined with satellite evidence, revealed groundwater replenishment in this dryland environment of central Tanzania occurs episodically from extreme seasonal rainfalls associated with El Niño climate events **[R3/R5]**. This outcome, together with a systematic review of the relationship between groundwater and climate

change **[R7]**, catalysed a pan-tropical analysis consistently tracing the origin of groundwater to extreme, heavy monthly rainfalls **[R4]**.

Taylor then led the most comprehensive analysis of the relationship between groundwater and climate ever undertaken in Africa **[R6]**, amassing 14 multi-decadal records of groundwater levels and rainfall from nine countries along an aridity gradient from hyper-arid to humid. Supported by Post-Doctoral Fellows Cuthbert and Shamsudduha, this study comprehensively established groundwater recharge in tropical Africa derives from statistically extreme heavy rainfall that in many environments is associated with predictable, large-scale modes of climate variability, such as the El Niño Southern Oscillation. Further, this empirical study showed that episodic groundwater recharge observed in tropical drylands is greater than that estimated by hydrological models that exclude recharge from ephemeral streamflow in drylands. In doing so, this research has undone the 'high certainty' consensus of the last (5th) assessment of the Inter-governmental Panel on Climate Change (IPCC) that climate change will decrease groundwater resources in dryland environments of tropical Africa. Detailed characterisations of the processes of groundwater recharge from ephemeral streamflow in Dodoma, Tanzania and the Ghoulbi-Maradi region of Niger **[R6]** led by Taylor under *GroFutures* [i] inform strategies to protect, sustain, and amplify groundwater replenishment.

Collectively, Taylor's research outcomes provide fundamental evidence informing the resilience of groundwater resources in tropical Africa to climate variability and change. His research shows the intensification of precipitation brought about by global warming and observed most acutely in the tropics, often serves to promote groundwater replenishment.

3. References to the research (indicative maximum of six references)

R1. Owor, M., **Taylor, R.G.**, Tindimugaya, C. and Mwesigwa, D. (2009). Rainfall intensity and groundwater recharge: evidence from the Upper Nile Basin. ***Environmental Research Letters***, Vol. 4, 035009. doi:10.1088/1748-9326/4/3/035009 - arose from grant **[ii]**

R2. MacDonald, A., Bonsor, H.C., O Dochartaigh, B.E. and **Taylor, R.G.** (2012). Quantitative maps of groundwater resources in Africa. ***Environmental Research Letters***, Vol. 7, 024009. doi:10.1088/1748-9326/7/2/024009- arose from grant **[iii]**

R3. Taylor, R.G., Todd, M., Kongola, L., Nahozya, E., Maurice, L., Sanga, H. and MacDonald, A. (2013). Evidence of the dependence of groundwater resources on extreme rainfall in East Africa. ***Nature Climate Change***, Vol. 3, 374-378. doi:10.1038/nclimate1731 - arose from grant [iii]

R4. Jasechko, S. and **Taylor, R.G.** (2015). Intensive rainfall recharges tropical groundwaters. ***Environmental Research Letters***, Vol, 10, 124015. doi:10.1088/1748-9326/10/12/124015 - arose from grant [iii]

R5. Kolusu, S.R., **Shamsudduha, M.**, Todd, M.C., **Taylor, R.G.** Kashaigili, J.J., Ebrahim, G.Y., **Cuthbert, M.O.** (2019). The El Niño event of 2015–16: Climate anomalies and their impact on groundwater resources in East and Southern Africa. ***Hydrology and Earth System Science***, Vol. 23, 1751-1762. doi:10.5194/hess-23-1751-2019 - arose from grants [i] and [v]

R6. Cuthbert, M.O., Taylor, R.G., Favreau, G., Todd, M.C., **Shamsudduha, M.**, J. Kashaigili, D. Seddon, Y. Nazoumou, N. Kukuric (2019). Observed controls on resilience of groundwater to climate variability in sub-Saharan Africa. ***Nature***, Vol. 572, 230–234. doi:10.1038/s41586-019-1441-7 - arose from grants [i] and [v]

R7. Taylor, R.G., Scanlon, B.R., Doell, P., Rodell, M., van Beek, L., Wada, Y., **Shamsudduha, M.**, Hiscock, K., Yeh, P., Holman, I. and Treidel, H. (2013). Groundwater and climate change. ***Nature Climate Change***, Vol. 3, 322-329. doi:10.1038/nclimate1744

All outputs were peer reviewed.

Grants

i.NERC-ESRC-DFID (NE/M008932/1) *GroFutures: Groundwater Futures in sub-Saharan Africa,* GBP1,900,000 (2015-2020) http://grofutures.org/

ii.NERC (NE/E001890/1) *QUEST-GSI: Global-scale impacts of climate change: an integrated multi-sectoral assessment*, GBP1,700,000 (2007-2010)
iii.DFID (GA/09F/094) *Groundwater resilience to climate change in Africa,* GBP284,000 (2010-2011)
iv. The Royal Society – DFID (AQ140023) *AfriWatSan: Sustaining urban groundwater-fed water supplies and sanitation systems in Africa,* GBP1,2000,000 (2015-2021) http://afriwatsan.org/
v.The Royal Society & Leverhulme Trust Senior Fellowship (LT170004) *Groundwater and climate in Africa: assessing new in-situ observations and models*, GBP51,000 (2017-2018)

4. Details of the impact (indicative maximum 750 words)

Taylor's research characterising the volume, renewability, and climate-resilience of groundwater resources in tropical Africa has had significant impact on the pursuit of water security regionally and nationally (Uganda, Tanzania, Niger), where Taylor has formed long-term partnerships with government ministries and research institutions. His research has led to a shift in the policy landscape, informing new groundwater-based solutions toward the realisation of UN Sustainable Development Goals 2 (zero hunger) and 6 (universal access to safe water and sanitation) that are more resilient to climate change **[A-F]**. This impact has been facilitated by:(1) Taylor's early and sustained engagement of water users including farmers and government departments in capacity-strengthening exercises, knowledge co-production, and delivery of policy briefs (Ethiopia, Kenya, Niger, Senegal, South Africa, Tanzania, Uganda); (2) Taylor's sustained dialogue with water ministries across Africa as co-administrator of the UKRI UPGro programme (2014-2020) that led to the re-establishment of AMCOW Groundwater Commission at 7th African Water Week in Gabon (November 2018); and (3) Taylor's engagement with the UN and other global agencies as Chair of the International Association of Hydrogeologists's Commission on Groundwater and Climate Change (2009-2018).

Informing adaptation to climate change in sub-Saharan Africa and global tropics:
Taylor's research is shaping global strategies to adapt to the impacts of both climate change and the rapid development of freshwater resources and demand in low-income countries in the tropics. The IPCC **[A]**, African Ministerial Council on Water (AMCOW) **[B]** Overseas Development Institute (ODI) **[C]**, UN Environment **[D]** and UN Water **[E]**, and Governments of Switzerland **[F]** Uganda **[G]**, Tanzania **[H]**, Niger **[I]** and all recognise and cite Taylor's evidence of the natural resilience of groundwater resources to climate change that enables the realisation of UN SDGs 2 and 6 in Africa. The most recent 5th Assessment Report of the IPCC cites **[R7]** and **[R4]** (in Chapter 3 'Freshwater Resources') in its discussion of the projected rise in groundwater withdrawals for irrigation under climate change and the resilience of groundwater to climate change associated with the bias in replenishment by heavy rainfalls amplified by climate change **[A]**. As recognised by the Executive Secretary of AMCOW, "The recent pan-African study of groundwater recharge led by Taylor **[R6]**…provides the most compelling evidence to date of the resilience of groundwater to climate change in Africa as well as new evidence of groundwater replenishment in African drylands where groundwater is often the only perennial source of freshwater" **[B]**. The 2014 ODI report 'Adaptation to Climate Change in Water, Sanitation and Hygiene Assessing risks, appraising options in Africa' cites **[R2/R4/R7]** in discussing use of groundwater to expand access to safe water in Africa under climate change **[C]**. In 2019, UN Environment cited Taylor's research **[R2]** in their report 'GEO-6: healthy planet, healthy people 2019, Analysis & Policy Observatory' **[D]** recommending use of groundwater as a future source of freshwater in Africa to sustain drinking water and food supplies. In 2020, UN Water cited Taylor's work **[R6/R7]** in describing the risks posed by climate change to groundwater **[E]** and heightened renewal of recharge associated with the amplification of rainfall intensities under climate change. This take up of Taylor's research by global agencies has led to specific in-country impacts in Uganda, Tanzania and Niger.

Informing groundwater development policies in Uganda: The Government of Uganda is known internationally for its science-led policies and policy instruments used to develop and manage water resources. Through a collaborative research partnership with the Ugandan Ministry of Water and Environment (MWE) since 2000, Taylor's modelling of groundwater resources in weathered crystalline rock environments **[R1]** underlying 80% of Uganda and quantitative

mapping procedures **[R2]** have informed the MWE's national-scale understanding of its groundwater resources. As the Commissioner of Water Resources Planning and Regulation puts it: "A continued programme of collaborative research with Richard has led to a number of invaluable outcomes that include, among others, an understanding of what controls the distribution of shallow groundwater resources in Uganda, and estimation of groundwater recharge in Uganda including a bias observed in groundwater recharge to heavy rainfall" **[G]**. Over the last seven years, these have continued to inform pioneering groundwater development policies that employ district-level water resources maps to guide the most cost-effective and sustainable groundwater development by government agencies (e.g. National Water and Sewerage Corporation), NGOs (e.g. WaterAid), and the private sector. Specifically, these maps detail at the district-level the options for water supply development, such as protection of spring discharges, drilling of shallow or deep wells, or use of treated surface water. These maps have influenced development practice nationally and regionally sparking a shift over the last decade from the construction of deep and more costly boreholes to shallow, less-expensive and more productive wells where hydrogeological conditions permit.

Further, research led by Taylor assessing groundwater recharge in Uganda under *AfriWatSan* [iv], The Royal Society Fellowship [v] and grant from DFID [iii] has established benchmarks, quantitatively and methodologically, in understanding the renewability of groundwater resources and their resilience to climate variability and change **[R1/R2/R4/R6]**. These research outcomes now inform Uganda's climate change adaptation strategy in water resources. The Commissioner of Water Resources Planning and Regulation at the Ugandan Ministry of Water and Environment confirms: 'The finding of a bias in groundwater recharge to heavy rainfall has provided a clear rationale for the use of groundwater as a climate-resilient source of freshwater in our National Adaptation Plan of Action to climate change and second and third National Development Plans (2005 to present)' **[G]**.The Commissioner confirms that 'As a result [of Taylor's research], Uganda has made great strides in improving and sustaining access to safe water in rural and urban areas, which is largely based on groundwater, with the current water supply coverage being 71% and 79% in rural and urban areas respectively' (from 65% in rural areas and 70% in urban areas in 2012/13) **[G]**.

Building climate resilience of the water supply to Tanzania's capital city: In 2015, the Government of Tanzania mandated the relocation of all government ministries from Dar es Salaam to the nation's capital, Dodoma, in central Tanzania. The water supply consequences of this decision have placed exceptional pressure on the sustainability of groundwater abstraction from the Makutapora Wellfield supplying safe water to Dodoma. Collaborative research led by Taylor under GroFutures and other projects over the last decade **[R3/R5/R6]** with the Tanzanian Ministry of Water (WamiRuvu Basin Water Board, WRBWB), Sokoine University of Agriculture (SUA), and Dodoma Urban Water Supply and Sewerage Authority (DUWASA) has, in the words of Tanzania's Director of Water Resources, "informed us of just how crucial seasons of extreme heavy rainfall, often associated with El Niño events, are to the replenishment of the Makutapora Wellfield supplying safe water to Dodoma" **[H]**. Further, the Director of Water Resources states, "these findings have helped to inform discussion and debate within the Ministry around the long-term future of the water supply for Dodoma. In response, the Ministry is evaluating the feasibility of amplifying Managed Aquifer Recharge to the wellfield. The work of Taylor and colleagues in resolving the timing and processes of recharge provide a rationale and benchmark for this evaluation".

Climate-resilient development policies to improve food security and access to safe water in Niger: GroFutures [i] research led by Taylor in Niger since 2015 with GroFutures co-PI Professor Nazoumou of the Université Abdou Moumouni de Niamey has provided detailed characterisations of the processes of groundwater recharge in Dodoma, Tanzania and the Ghoulbi-Maradi region of Niger **[R6]**. It has placed groundwater centrally in national strategies to alleviate poverty and to improve the resilience of drinking-water supplies and agricultural production to the impacts of climate change **[I]**. In 2016, Nazoumou organised an event at COP22 for the President of Niger and other stakeholders, including the World Bank and African Development Bank, "to showcase Niger government's programmes and activities in terms of

climate adaptation and resilience in rural areas". Nazoumou discussed "GroFutures and how groundwater-fed irrigation can be developed in Niger where surface water is limited and highlight greater resilience of groundwater resources to climate change" **[I]**. Nazoumou is a member of the Niger National Commission for Water and Sanitation and the Steering Committee of the National Action Plan on Integrated Water Resources Management (PANGIRE). PANGIRE's last report cites research led by Professor Nazoumou under GroFutures: "the total potential of irrigable land should be revised upwards (PANGIRE, 2017), in particular taking into account the possibilities of low-cost exploitation of the most accessible and renewable freshwater source, groundwater" (Nazoumou et al., 2016)" **[I, p. 23]**. In 2019 Taylor raised awareness of the resilience of groundwater to climate change in an article for The Conversation drawing on **[R2]** and **[R6]** which was read by 5,758 and republished by Yahoo News **[J]**.

Taylor's research providing robust evidence on the volume, renewability, and location of groundwater resources informs climate-resilient strategies to sustain increased access to safe water and the expansion of irrigated agriculture across tropical Africa in pursuit of UN Sustainable Development Goals 2 and 6. This research has helped to improve access to safe water in rural and urban areas, to inform the sustainability of the water supply to Tanzania's rapidly growing dryland capital city, and to expand small-scale irrigation and access to safe water in rural Niger.

5. Sources to corroborate the impact (indicative maximum of 10 references)

A. IPCC 5th Assessment Report (2014) WGII Chapter 3: *Freshwater Resources, o*nline: https://bit.ly/2OBMDJc. See p. 241, 244

B. Testimonial Statement from the Executive Secretary of the African Ministerial Council on Water (AMCOW)

C. Overseas Development Institute (ODI), DFID (UK): *Adaptation to Climate Change in Water, Sanitation and Hygiene Assessing risks, appraising options in Africa,* online: https://bit.ly/3l0xRI5. See pp. 5-6

D. UN Environment Global Environment Outlook – *GEO-6: healthy planet, healthy people 2019, Analysis & Policy Observatory (APO)*, online: https://bit.ly/3t3LBEQ. See p. 240 (Full report available on request)

E. UN World Water Development Report 2020: *Water and Climate Change*, online: https://bit.ly/3t0zR66. See pp. 53, 128

F. Federal Office for the Environment (FOEN), Switzerland: *Climate change and freshwater ecosystems: impacts on water quality and ecological status,* online: https://bit.ly/2OysKmC. See p. 25

G. Testimonial Statement from the Commissioner of Water Resources Regulation in the Ugandan Ministry of Water and Environment; Second National Development Plan (NDPII) 2015-16-2019/20.

H. Testimonial Statement from the Director of Water Resources in the Tanzanian Ministry of Water and Irrigation

I. République du Niger: *Stratégie et Plan National d'Adaptation face aux changements climatiques dans le secteur Agricole* / Republic of Niger: *Strategy and National Adaptation Plan in the face of climate change in the Agricultural sector* (SPN2A 2020-2035, 2020), online: https://bit.ly/3qv4KxN, translated from "*Cependant, le potentiel total de terres irrigables devrait être revu à la hausse (PANGIRE, 2017), notamment en tenant compte des possibilités d'exploitation à faible coût des eaux souterraines renouvelables les plus accessibles* Interview with Nazoumou https://bit.ly/3el2yqn. Available on Request

J. Media coverage in *The Conversation* and Yahoo News