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Rice Production with Restricted Water Usage: A Global Perspective

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GLOBAL rice production remains critically import for food security; however, fresh water is an ever-increasingly diminished resource. The objective of this manuscript is to select central and comprehensive research focusing on rice production and diminished water availability to isolate and authenticate emerging initiatives to address continuance of rice production and to ensure water sustainability. Three regions were selected: (i) Asia with an emphasis of China and India, (ii) The United States of America and (iii) The Mediterranean region with an emphasis on Egypt. Each of these regions recognize current or emerging issues associated with water quantity, water quality, urbanization, climate change and other technological, social and policy constraints; however, each region has a different hierarchy of issue importance. China and India recognize climate change, aquifer overdraft and pollution of water resources as central issues, whereas the mid-South region of the United States of America is more focused on irrigation technology to improve farm profitability. Egypt is primarily focused on water quantity and quality limitations, with substantial research addressing desertification and saline soils/water. This review focuses on stated research objectives in compelling, peer-reviewed literature to indicate regional approaches addressing the causes of restricted water availability for rice production and the most-probable approaches for maintaining rice production to safe-guard food security and producer profitability. Thus, unique rice water management approaches are predicated on the region's water quantity and quality environmental assessment.

Keywords: Rice, Water, Egypt, India, China, United States.

Introduction

Global rice (*Oryza sativa*) production has been steadily increasing to the current 2019 production value of 501 million metric tons (USDA-ERS, online). Global rice is currently planted on 154 million ha, requiring approximately 11% of the worlds cultivated land; however, rice culture consumes approximately 80% of the total irrigated fresh water (Wu et al., 2017). Bouman et al. (2006) determined that 34 to 43% of the worldwide freshwater resources are employed for irrigation of paddy rice. Rice production in the United States in 2018 centered near 11.4 million metric tons, with approximately 50% of the production exported. The increased USA rice production is commonly correlated with population growth, alternative commodity prices, market and export opportunities.

Both surface and groundwater resource usage are increasing because of climate change, rapid industrialization, urbanization, agricultural irrigation, heavy metal contamination, land tenure and other social and technological issues. Issues concerning water and soil quality are inextricably linked. While concentrating on three dominant rice producing regions, this manuscript (i) Isolates and specifies emerging water quantity and quality limitations involving irrigated rice production and (ii) Details the soil and rice agronomic research addressing current or projected restricted water

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usages. An outcome of this manuscript illustrates regional dimensions of sustaining food security and providing technology to continually augment food production.

Water resources and rice production across Asia, with an emphasis on people's Republic of China (China) and Republic of India (India)

In 2006, China had 62.9 million ha having full irrigation, with 69% of the irrigation dependent on surface water sources and recycled wastewater and 31% dependent on groundwater sources (Food and Agriculture Organization of the United Nations. 2016. AQUASTAT. China). Rice irrigation accounts for 31.3 million ha. Udimal et al. (2017) documented how both water quantity and quality issues are limiting usage of both surface and groundwater freshwater resource utilization, features attributed to pollution impacts and aquifer overdraft. Concerns involving climate change (increased instances of episodic drought/floods), urbanization, industrialization and population migration and their subsequent influence on irrigation of agricultural lands is influencing both research objectives and governmental policies.

In 2011, India had 169.6 million ha of cultivated land, with 76.8 million irrigated ha (FAO, 2016). Irrigated rice production accounts for 22.4 million ha. India has a typical monsoon climate, with the two northeast and southwest monsoons accounting for 70 to 95% of the annual rainfall. Given the large geographic area, rainfall patterns show both spatial and temporal variability. The Himalayas supply glacial snowmelt to major river systems, including Ganges, Brahmaputra and Indus rivers. Other river systems are predominantly rainfall dependent. In 2010, total water withdrawal was 761 billion m^3/yr, with agriculture usage (irrigation and livestock) consuming 688 billion m^3/yr, municipalities consuming 56 billion m^3/yr and industry consuming 17 billion m^3/yr. Non-conventional sources of water include produced wastewater (25.4 billion m^3/yr) and reused agricultural drainage water (113.5 billion m^3/yr) (FAO, 2016). Climate change associated with annual Himalayan glacial snowmelt reductions and aquifer overdraft are major concerns influencing agricultural and economic development. Across Asia, hydroelectric dam construction is altering local hydrology and irrigation potential, compound future water availabilities especially where rivers cross national boundaries.

Associated critical literature addressing water-rice issues in East Asia

Carrijo et al. (2016) performed a compelling rice meta-study involving 56 studies comparing continuous flood with alternate wetting and drying (introduction of unsaturated soil water conditions), with most of the studies derived from Asia. They defined and partitioned alternate wetting and drying irrigation regimes into "safe" or "mild" (where the soil water matric potential was equal to or smaller than -20 kPa) and "severe" (where the soil water matric potential was below -20 kPa). The meta study documented the following: (i) The presence of unsaturated soil water conditions imposed during the entire growing season depressed rice yields, whereas unsaturated soil water conditions prior to either heading only (vegetative) or post heading (reproductive) only demonstrated little to zero yield loss, (ii) In most cases mild or safe alternate wetting and drying do not depress rice yields, whereas severe alternate wetting and drying showed yield reductions, (iii) Yield losses were more significant in low organic matter soils or soils having alkaline pH levels, (iv) Compared to the continuous flood system the alternate wetting and drying systems exhibited smaller water use rates and where mild alternate wetting and drying was practiced the water use efficiency was greater.

Trisurat et al. (2018) conducted simulations using climate data, irrigation capacity, agronomic practices, variety selections and alternative crops to estimate futuristic rice yields and water consumption values across the lower Mekong Basin. Episodes of extreme drought may become more common and the impact will be greatest in Thailand, followed by Lao PDR and Cambodia, with the smallest impact in Vietnam. In Thailand, Gheewala et al. (2018) used estimates for future water stress index values to isolate critical areas for water stress and to propose land-use policy changes and cropping systems to off-set anticipated water stress in those critical areas.

In China, Tao et al. (2013) observed climatic records from 1991 to 2000 and from 2000 to 2009 to chronicle rice production climate-based disasters. Rice disasters attributed to drought, flooding, heat stress, chilling damage, and insects/diseases were compared between the time intervals, with the inference that climatic differences were accelerating, and climate extremes would impact food security.

In southeastern China, Yang et al. (2017) pursued a water management program wherein rice production irrigation systems were compared to assess rice yields, irrigation water use efficiency, soil respiration and net ecosystem CO_2 exchange between croplands and the atmosphere. They documented that controlled irrigation employed only 46% of the water commonly used by flood irrigation, yet rice yields were comparable between the irrigation strategies, thus irrigation water efficiency was substantially improved. Controlled irrigation exhibited higher rates of soil respiration (CO_2 transfer from soil to atmosphere) especially prior to rice heading; however, methane production was greater for the traditional flood irrigation.

In an arid region of China, He et al. (2016) compared rice growth characteristics and yields in flood and non-flood systems. Non-flood systems included (i) Drip irrigation frequencies with plastic mulch and (ii) Furrow irrigation with and without plastic mulch. Rice root length density, leaf dry weight, shoot dry weight and root activity were greater in the non-flood irrigation system at mid-tiller. Yields were typically greater in the flood system across all treatments. For the drip irrigation systems, the highest grain yield (approximately 8,900kg ha^{-1}) and the highest water use efficiency (0.63) were observed when the soil water contents were kept near -30kPa before panicle initiation and kept near -15kPa after panicle initiation. For this system, water use efficiency was 2.5 times greater when compared with the flood system.

Wu et al. (2017), in China, investigated double rice systems over 17 years featuring (i) Continuous flooding, (ii) Flooding with mid-season drying followed by flooding, (iii) Flooding followed by mid-season drying followed by intermittent irrigation without significant ponding and (iv) Flooding followed by rain-fed. For both the early-season and late-season rice crops the flooding system involving mid-season drying followed by flooding had the largest water irrigation usage, whereas flooding followed by rain-fed system had the smallest water irrigation usage. The continuous rice system had slightly greater rice yields during both early- and late-seasons; however, for the early-season rice crop the continuous flood system is preferred for both yield and water use efficiency and for the late-season crop the flooding followed by mid-season drying followed by intermittent irrigation without significant ponding system was preferred for yield and water use efficiency.

Cheng et al. (2013) observed a Chinese rice-wheat rotation with an emphasis on determining the influence of warming temperatures on yield potential and water use. Plots featuring the rice-wheat rotation were artificially warmed, showing that for each of the three years rice yields declined approximately 13%, evapotranspiration increased approximately 23% and the surface soils Ap layer exhibited a soil organic matter decline. Kuo (2014), in Taiwan, observed various calendar-specific rice irrigation schedules, documenting that a 10-day irrigation schedule may be an acceptable compromise between yield and water scarcity. In China, Wang et al. (2017) addressed challenges from increased occurrences of drought by observing: (i) How producers respond to drought through irrigation, (ii) The capacity of local irrigation infrastructures and (iii) The effectiveness of the producer's irrigation responses. By surveying 85 villages across five provinces, Wang et al. (2017) demonstrated that irrigation infrastructure was supportive of producer's responses to drought-induced water scarcity and that yield thresholds were risk protected. Peng et al. (2012), in south China, investigated water use efficiency and pollution impacts of irrigation and controlled drainage. In their study, they demonstrated that an integrated irrigation and a controlled irrigation system supported water productivity and that nitrogen and phosphorus transport from production fields were substantially reduced.

Associated critical literature addressing water-rice issues in South Asia

Raj et al. (2017) conducted a multi-year and large-scale upland and lowland rice project during wet seasons in the Eastern Indo-Gangetic Plains (India). The project featured (1) Main plots of (i) Dry direct seeded rice, (ii) A rice intensification system and (iii) A puddled and transplanted rice system with all three main plots factorially positioned with (2) Sub-plots consisting of five varieties. As expected, lowland rice exhibited 13% better yield and a greater net producer economic return. Yields for the rice intensification system were superior to those of the dry direct seeded and puddled transplanted rice systems. Based on the yield data, the rice intensification system provided the optimum total water productivity. Varieties were also shown to be important yield predictors.

Singh et al. (2018), in India, observed rice production on sodic soils having treatments involving (i) A traditional farmer-use irrigation practice, (ii) Sprinkler irrigation and (iii) A low energy water application device. Sub-treatments involved irrigation frequency. The highest rice yields and water savings were observed for (i) The water application frequency of two-days after disappearance of ponded water and (ii) The use of sprinkler technologies.

Das et al. (2018), in India, conducted a multi-year trial involving a modified system of rice intensification with the goal of increasing cropping intensity, yields, water productivity and producer livelihood. Rice production was increased 39% in the modified system of rice intensification compared to traditional practices. Net returns to producers were similarly increased by 61% and water use efficiency increased by 12%. Given that the modified system of rice intensification permitted a more rapid crop development, a second cropping of vegetable pea (*Pisum sativum*) was substantially important to the economic return of the local producers.

Behera & Panda (2013), in India, assessed rice production to observe the effect of nitrogen, phosphorus and potassium fertilization on rice growth and its subsequent influence on water utilization and nutrient leaching. Their 3-year study goal was to increase water use efficiency and mitigate nutrient losses in a sub-humid to sub-tropical climate. Fertilizer application rates increased rice grain yield, straw yield and leaf area index; however, fertilization amendments did not influence water loss rates. Nitrogen was key to improving biomass production and yield, thereby improving water use efficiency. In their study, a $N:P_2O_5:K_2O$ rate of 80:40:40kg/ha was optimal. Jha et al. (2017), in India, conducted a field-based lysimeter study to show that average deep percolation water losses were 35% of the total water application; however, deep water percolation and nitrogen leaching could be substantially reduced by a shallow water ponding regime.

In India, Mishra et al. (2012) conducted a 15-year study observing canal water-delivery schedules separated across monsoon and dry seasons. Water delivery schedules consisted of continuous flow and alternate delivery schedules. During the monsoon, water delivery schedules of 15 days with water delivery alternating with 15 days without water delivery were most efficient in optimizing evapotranspiration and yield; whereas, during the dry season, water delivery schedules of 7 days with water delivery alternating with 7 days without water delivery were most efficient in optimizing evapotranspiration and yield. Two varieties were assessed and the highest yields were 4.92tons ha^{-1} and 4.46tons ha^{-1}, respectively. Concerning Sri Lankan rice production, Davis et al. (2016) predicted that rice intensification will support food security through 2050, providing population growth occurs at predicted rates. However, their rice intensification estimates are predicated on increases in water application rates and compensating water use efficiency augmented by increased fertilizer use.

Water resources and rice production in the United States of America (USA)

The mid-south region of the United States (portions of Arkansas, Mississippi and Missouri along the Mississippi River) and Louisiana and Texas (along the Gulf of Mexico) and the Central Valley of California are the principle rice growing regions. In 2012, USA rice production was 9 million metric tons. Typical yields in the mid-South annually vary from 6 to 8 metric tons/ha. California water issues include (i) Inability to drain irrigated soils having elevated water tables that have become saline and (ii) Increasing water demands from urban centers. In portions of Arkansas, Texas and Mississippi aquifer overdraft is a looming agricultural issue. Other issues involve (i) Reducing arsenic uptake in rice with furrow irrigation, (ii) Reducing methane release from the soil to the atmosphere, (iii) Reducing nutrient transport in surface drainage water and (iv) Improving nitrogen and water use efficiency.

Associated critical literature addressing water-rice issues in the United States of America

In a series of manuscripts, Aide et al. (2016, 2017) and Aide (2018, 2019), in the lower Mississippi River embayment, documented rice research involving furrow rice irrigation. Furrow rice irrigation involves land grading with a raised bed configuration (typically with 0.83-meter bed spacings) and the episodic application of water between the raised beds using polypipe across the field edge. Rice is drill seeded and irrigation commences at the 5th leaf stage after application of approximately 130kg urea ha^{-1}, followed by supplemental nitrogen at internode elongation. Furrow irrigation of rice is perceived as an alternative to permanent flood post 5th leaf stage because (i) Land graded fields already exist because of crop rotations, (ii) Reduced reliance on levees, (iii) The prospect of smaller total water application reduces the specter of aquifer overdraft and (iv) Reduced rough (paddy) rice seed arsenic concentrations. Producer concerns employing furrow irrigated rice include (i) Reduced yields, (ii) Nitrogen loss because of nitrification-denitrification, (iii) Increased weed pressure (ponded water is a great herbicide) and (iv) Increased likelihood of the rice disease, notably blast disease. From 2016 to 2019 rice yields were slightly to significantly negatively impacted in furrow irrigation compared to delayed flood irrigation; however, the number of the furrow irrigations is being adjusted and yields are becoming more comparable. Rice yields are also very variety dependent and producer variety selection is key to yield attainment and the avoidance of the incidence of blast. The use of urease and nitrification inhibitors in furrow irrigated rice is resolving issues associated with nitrogen use efficiency. For all trials, arsenic concentrations in rough (paddy) rice have declined from average near an average of 0.24mg as kg^{-1} to 0.05 mg as kg^{-1} (Aide et al., 2016; 2017; 2018; 2019).

In the midsouth USA, Atwell et al. (2018) investigated (i) Continuous flood (drill-seeded, delayed flood at the 5th leaf stage), (ii) Straighthead irrigation, (iii) Alternate wetting and drying and (iv) Aerobic irrigation regimes across six varieties to assess maturity, mature plant height, nitrogen use efficiency and rice grain yield. Aquifer overdraft in this region is a growing concern. The aerobic irrigation system exhibited reduced yield (approximately 20%) and nitrogen use efficiency, whereas the remaining irrigation treatments demonstrated positive yield attainment and better nitrogen use efficiencies. Massey et al. (2014) observed farmer adaptation of intermittent flooding using multiple-inlet rice irrigation in Mississippi (USA), documenting that farmer acceptance is largely predicted on pumping costs, aquifer depletion and yield maintenance. Nalley et al. (2015) observed the economic viability of alternate wetting and drying irrigation for rice in Arkansas (USA) and noted that alternate wetting and drying irrigation improved water use efficiency 21 to 56%, which reduces aquifer overdraft. The Massey and the Nalley studies both documented reductions in methane release to the atmosphere with the imposition of alternate wetting and drying irrigation.

In California, Linguist et al. (2015) compared water seeding (partially germinated rice seed applied by airplane into paddy water) and dry seeding rice systems to ascertain differences in water consumption. The dry seeded rice system required less early-season water application when rainfall was sufficient to have only one flush (water application to promote seed germination); whereas there was no significant difference in early-season water consumption when two or more water flushes were required for seed germination. In another California study, Carrijo et al. (2018) investigated the influence of variable soil drying episodes in alternate wetting and drying irrigation systems on rice yields and grain arsenic accumulation. Yield was not reduced because of alternate wetting and drying, a feature attributed to soil water matric potentials having more soil moisture than -25kPa at the 25-35cm rooting depth. Grain arsenic concentrations in continuous flood and mild alternate wetting and drying episodes were much larger than the severe alternate wetting and drying episodes.

Water resources and rice production across the Mediterranean region, with an emphasis on the Arab Republic of Egypt (Egypt)

Approximately 98% of Egypt's freshwater resources originate outside of its borders, most notable is the Nile River and aquifers, some of which span across national borders. Aquifers include: (i) The Nile aquifer, (ii) The Nubian sandstone aquifer, (iii) The Fissured aquifer, (iv) The Moghra aquifer, (v) The Coastal aquifer and (vi) The Hardrock aquifer. Other important water sources are the reuse of agricultural drainage water and treated municipal wastewater (FAO, 2016). Cultivated land encompasses 3.76 million ha (4% of the total national land area). The landscape near the Nile River possesses a dense network of canals, including mesqas (privately owned ditches important to distributed water to family-owned farms). Drainage water in the Nile Delta (Delta) is estimated to be approximately 16 billion M^3/year, of which approximately 40% is re-applied to agricultural lands. Irrigated rice (2010) constituted 452,000ha out of 3.6 million total irrigated ha. Rice production is also considered critical to impede subsurface salt-water intrusion. Soil salinization is a critical concern.

Associated critical literature addressing water-rice issues in the Mediterranean region

Egypt has a compelling research history focusing on assessing and managing their soil and water resources and employing technology to address climate change. Elbasiouny (2018) performed an assessment of environmental sensitivity, soil quality and sustainability across the Egyptian north delta region to isolate current and anticipated desertification alterations. Environmental sensitivity was simulated using MEDALUS (Mediterranean Desertification and Land Use), a software-based model employing four thematic fields: (i) Climate, (ii) Vegetation, (iii) Soil and (iv) Land management. Employing GIS, the four thematic fields were partial indicators that were integrated into a complex sustainability index. Much of the study area was classified as critical (fragile) environmentally sensitive areas that are likely experiencing soil quality degradation. Furthermore, in the Delta region, Saied et al. (2017) evaluated in-farm soil management practices for improving soil resources and agricultural productivity for rice and wheat. The presence of salt-affected soils were treated with (i) Gypsum, (ii) Manure and/or biofertilizer with various sources of synthetic nitrogen (urea, anhydrous ammonia, and ammonium sulfate). Some soils were mole-drained to encourage deeper root penetration and leaching. Salt leaching was optimized using gypsum with ammonia injection; however, other gypsum treatments coupled with other nitrogen sources also were salt-leaching effective. The highest infiltration rate was observed with gypsum, ammonia injection with mole drain incorporation. Post treatment soil property evaluation showed that gypsum, ammonia injection, and mole drain placement improved bulk density and porosity.

Rashed (2014) investigated the suitability of irrigation and drainage waters in the south El-Kalubia Governorate for sustainable agricultural development across soils experiencing salinization. Electrical conductivity measurements indicated many waters exhibit high to very high salinity hazards and some of the water samples also exhibited elevated sodium adsorption ratios. One corrective land management involves the proper blending of drainage and canal water to foster irrigation waters more suited to long-term soil resource sustainability. In their study area, a slight majority of the soils were saline non-sodic, whereas the remainder of the soils were non-saline non-sodic. Abdel-Fattah & Helmy (2015) assessed wastewater quality for irrigation suitability in the east Delta. Their perspective was to characterize drainage waters for salinity to apply these waters appropriately to soils having differences in drainage/permeability and the culture of crops having different tolerances to salinity. None of the waters were characterized as having sodicity limitations.

In the Delta's Wasat region, Aly et al. (2013) reinforced the need to improve irrigation water delivery infrastructures, particularly that of tertiary canals (meskas). Water user associations are private and farmer managed entities to regulate the local improved meskas to guarantee proper maintenance and an equable water distribution. At Luxor, Egypt, Ahmed et al. (2014) reviewed existing and future water consumption use among agricultural, residential, institutional, commercial and tourist entities, noting that policies are required for the management of water supply and demand. While discussing the geology and hydrology of Egypt's groundwater, El-Tahlawi et al. (2008) comprehensively reviewed the environmental impacts that are occurring and their impact on Egypt's groundwater. The main groundwater environmental impacts include: (i) Differences in the quantity and quality of groundwater availability across Egypt, (ii) Overuse and underuse of groundwater because of differences in population distributions, especially in rapidly increasing urban centers, (iii) Water potability and sanitation and (iv) Continuing decrease in per capita water resources. Hereher & El-Ezaly (2012) documented saline and saline-sodic soil conditions along the Red Sea Coast.

In the Siwa Oasis (Egypt), Aly (2014) employed the Saltmed model to observe the impact of shallow groundwater fluctuations and soil salinity in irrigation management. Shallow groundwaters and high evapotranspiration ratios are appreciably responsible for soil salinization and irrigation waters are largely responsible for soil sodicity. Application of the Saltmed model demonstrated reduced irrigation water applications remained appropriate for profitable olive crop production and soil salinity reductions were realized. Aboukhadrah et al. (2015) observed 25 rice genotypes cultured under continuous flooding and irrigation every 12 days. The research intent was to identify desirable cultivars for breeding that supported drought resistance. Varieties were identified that possessed high yield plant^{-1} and other important yield components under both normal and drought conditions.

El-Hassan (2018) observed that land fragmentation in the Delta was correlated with rice field total water application, suggesting that irrigation and farm water contracting systems could be better employed to improve water use efficiency. King & Salem (2012) presented an interdisciplinary analysis of multiple small and large farms in the western desert of Egypt on their usage of shallow groundwater. Their findings indicate that larger-sized farms increasingly utilize non-renewable groundwater. They recommended policy initiatives that support long-term sustainability of the multi-layer aquifer system and maintaining a balance of larger and more profitable farms and smaller-sized family operations.

Djaman et al. (2018) observed the effects of alternate wetting and drying irrigation and nitrogen fertilization practices on rice yield in the Sahel. Water scarcity was seasonally attributed to elevated pumping costs and high evapotranspiration rates, fostering interest in developing alternative irrigation strategies to reduce water application rates and improve water use efficiencies. An experimental design having multiple rice varieties, each with five distinct nitrogen fertilizer rates at various intensities of water stress imposed by alternative wetting and drying was performed. The alternative wetting and drying irrigation regime having a soil water matric potential of -30kPa achieved 12 metric tons ha^{-1} at 150kg N ha^{-1}. In general, the alternative wetting and drying irrigation regime reduced rice water usage and enhanced nitrogen use efficiency and yield attainment.

Conclusion

Selecting China and India as partially representative across Asia and focusing on water utilization in rice production, the dominant research intention is to improve water use efficiency while maintaining yields, with alternate wetting and drying receiving the greatest research investment. Faced with climate change, aquifer overdraft, water quality degradation, expanding rural to urban migration and improved infrastructure challenges, research investments are accordingly directed. Governmental policy and associated regulation governing water distribution is also integral to water security.

In the USA, research focus is skewed towards (i) Improving water efficiency, (ii) Water quality initiatives and (iii) Environmental issues of CO_2 and methane release (Linguist et al., 2014). Except for selected areas in the mid-South where aquifer overdraft is reducing water yield, the increasing use of furrow irrigated rice has attracted producer interest more for its potential to increase farm profitability that to reduce water utilization. The use of unmanned aerial vehicles equipped for remote sensing and the use of surge-valves for side-inlet irrigation represent the technology research investments.

Selecting Egypt as partially representative for North Africa and other Mediterranean nations and focusing on water utilization in rice production. The dominant research intentions include: (i) Improving soil quality because of desertification (including salinization and sodification), (ii) Water quantity (including limiting aquifer overdraft and improving irrigation infrastructure), (iii) Water quality (including mixing soil drainage water with more pristine water sources) and (iv) Supporting food security by regulating crop production. Secondary research intentions include: (i) Irrigation efficiency, (ii) Rice breeding for drought and heat tolerance and (iii) Nation-wide assessment of soil and water resources using advanced mapping technologies.

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