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Conjunctive Water Management: Ways Forward to Sustainable Water Management in Response to Sustainable Development Goals

การจัดการน้ำผิวดินร่วมกับน้ำใต้ดิน: แนวทางสู่การจัดการน้ำสู่เป้าหมายการพัฒนาที่ยั่งยืน

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Abstract

Objectives: This article aims to investigate the role of conjunctive water management (CWM) in response to Sustainable Development Goals (SDGs) to address water challenges in the contemporary world.
Methods: This study analyzed secondary data related to CWM practices worldwide and their contribution to SDGs to elicit key problems in the CWM application and the key challenges of CWM to achieve the SDGs.
Results: CWM plays a key role in ensuring water security worldwide. However, key problems with the CWM application exist. This article shows the significance of the CWM approach, the challenges of nesting to single resource management, the roles of CWM in contributing to SDGs, and the ways forward for CWM to ensure water security toward SDG 6 (clean water and sanitation).
Application of this study: The findings will be useful for policymakers, practitioners, and multi-stakeholders in water management to apply the CWM guidelines to cope with water insecurity under anthropogenic and climate pressures. Furthermore, governments can develop the CWM framework and scale up collaborative actions for transboundary CWM to respond to SDGs.

Keywords: conjunctive water management, sustainable water management, transboundary water management, water governance, water security

บทคัดย่อ

วัตถุประสงค์: บทความนี้มีวัตถุประสงค์เพื่อตรวจสอบบทบาทของการจัดการน้ำผิวดินร่วมกับน้ำใต้ดินในการสนับสนุนต่อเป้าหมายการพัฒนาที่ยั่งยืนเพื่อจัดการกับความท้าทายด้านทรัพยากรน้ำในโลกร่วมสมัย
วิธีการศึกษา: บทความนี้วิเคราะห์ข้อมูลทุติยภูมิที่เกี่ยวข้องกับแนวทางปฏิบัติของการจัดการน้ำผิวดินร่วมกับน้ำใต้ดินทั่วโลกและบทบาทการสนับสนุนต่อเป้าหมายการพัฒนาที่ยั่งยืน เพื่อแสดงถึงปัญหาสำคัญและความท้าทายในการประยุกต์การจัดการน้ำผิวดินร่วมกับน้ำใต้ดินเพื่อให้สามารถบรรลุเป้าหมายการพัฒนาที่ยั่งยืน
ผลการศึกษา: การจัดการน้ำผิวดินร่วมกับน้ำใต้ดินมีบทบาทสำคัญในการสร้างหลักประกันความมั่นคงด้านน้ำทั่วโลก อย่างไรก็ตาม ปัญหาสำคัญในการประยุกต์ใช้หลักการจัดการน้ำผิวดินร่วมกับน้ำใต้ดินยังคงปรากฏอยู่ บทความนี้ได้แสดงถึงความสำคัญของแนวทางการจัดการน้ำผิวดินร่วมกับน้ำใต้ดิน ความท้าทายในการจัดการทรัพยากรน้ำ บทบาทการจัดการน้ำผิวดินร่วมกับน้ำใต้ดินในการสนับสนุนเป้าหมายการพัฒนาที่ยั่งยืน และแนวทางสำหรับการจัดการน้ำผิวดินร่วมกับน้ำใต้ดินในการสร้างหลักประกันความมั่นคงด้านน้ำเพื่อสนับสนุนเป้าหมายการพัฒนาที่ยั่งยืนข้อที่ 6 ในเรื่อง น้ำสะอาดและสุขอนามัย
การประยุกต์ใช้: ผลการศึกษานี้จะเป็นประโยชน์สำหรับผู้กำหนดนโยบาย ผู้ปฏิบัติงาน และผู้มีส่วนได้ส่วนเสียหลายฝ่ายที่เกี่ยวข้องกับการจัดการทรัพยากรน้ำในการดำเนินการประยุกต์ใช้แนวทางการจัดการน้ำผิวดินร่วมกับน้ำใต้ดินเพื่อรับมือกับความไม่มั่นคงด้านทรัพยากรน้ำภายใต้แรงกดดันจากมนุษย์และสภาพภูมิอากาศ นอกจากนี้ รัฐบาลสามารถพัฒนากรอบการจัดการน้ำผิวดินร่วมกับน้ำใต้ดินและขยายขอบเขตการดำเนินการร่วมกันในการจัดการน้ำผิวดินร่วมกับน้ำใต้ดินแบบข้ามพรมแดนเพื่อสนับสนุนเป้าหมายการพัฒนาที่ยั่งยืน

คำสำคัญ: การจัดการน้ำผิวดินร่วมกับน้ำใต้ดิน การจัดการน้ำอย่างยั่งยืน การจัดการน้ำข้ามพรมแดน การกำกับดูแลทรัพยากรน้ำ ความมั่นคงด้านน้ำ

Introduction

Water security has emerged as a major challenge worldwide (Allan et al., 2013; Srinivasan et al., 2017; UNESCO and UNESCO i-WSSM., 2019; Mishra et al., 2021; United Nations, 2021; Chapagain et al., 2022; World Bank, 2022; Babuna et al., 2023; United Nations, 2023). Over the last four decades, global water use has increased by 1% each year and is projected to rise similar rate by 2050 (United Nations, 2023). The driving forces (i.e. population growth, urban expansion, industrial development, agricultural intensification, and tourism development coupled with climate change) have currently pressured the states of water resources (quantity and quality) (Allan et al., 2013; Frone & Frone, 2015; Laino-Guanes et al., 2016; Muenratch et al., 2022; Wang et al., 2022; Avci, 2023; Qiu et al., 2023; Scanlon et al., 2023; Yadava et al., 2023). Simultaneously, many countries have faced water stress (Asif et al., 2023). Around 80% of individuals experiencing water stress resided in Asia, including northeast China, India, and Pakistan (United Nations, 2023). These challenges are urgently requested to be addressed in Sustainable Development Goals (SDGs) toward SDG 6 – clean water and sanitation (United Nations, 2023).

Water insecurity poses serious threats to many developing countries (Garrick & Hall, 2014; Aboelnga et al., 2019; United Nations, 2023). Water scarcity is one of the critical impacts, especially in irrigated and urban areas (Rockström et al., 2010; Warner & Diaz, 2022; United Nations, 2023). The global urban population confronting water scarcity is expected to grow from 933 million in 2016 to 1.7-2.4 billion people in 2050, with India expected to be the worst impacted (He et al., 2021; United Nations, 2023). Currently, around 25% of worldwide croplands face agricultural economic water scarcity, with the lack of irrigation caused by low institutional and economic capacity rather than hydrologic limits (Rosa et al., 2020; United Nations, 2023). Meanwhile, extreme events such as floods and drought are challenges to water management, especially in urban areas due to the lack of urban water planning (Aboelnga et al., 2019; Chapagain et al., 2022). Further, excessive water demand resulted in water use competition and conflicts among water users (Zhang, 2015; Safavi et al., 2016; Wu et al., 2016; Flörke et al., 2018; Teotónio et al., 2020). The limit of water access among marginalized and vulnerable groups still exists while the U.N. attempted to address “water for all” in the SDG6 targets (Bayu et al., 2020; London et al., 2021; Babuna et al., 2023; Rodríguez-Izquierdo et al., 2023; United Nations, 2023). Thus, good water governance is required to address complex water management (Pahl-Wostl et al., 2010; Gupta & Pahl-Wostl, 2013; Akamani, 2016; Pahl-Wostl et al., 2020).

Water governance is largely developed for assessment frameworks to ensure water security (see, Pahl-Wostl et al., 2010; Wiek & Larson, 2012; Gupta et al., 2013; Chan et al., 2016; Megdal et al., 2017; Adams et al., 2020; Molle & Closas, 2020; Di Vaio et al., 2021; Muenratch et al., 2022; Muenratch & Nguyen, 2022; Neto & Camkin, 2022; du Plessis, 2023). Although water governance can address complex water management, it is not the panacea for all countries. Hence, translating water governance to multiple scales is also significant for specific water management contexts (Ravnborg et al., 2012; Taher et al., 2012; Milman et al., 2018; Muenratch & Nguyen, 2022). Yet, the lack of collaboration across sectors and the community's participation in water planning are the significant barriers to good water governance in this century (Herrera, 2019; Carbonell et al., 2023; du Plessis, 2023; Stein et al., 2023). Thus, good water governance is a prerequisite to enhance water security and meet water demand by engaging social, and institutional aspects in the transition toward sustainable water management (Di Vaio et al., 2021; Neto & Camkin, 2022; Babuna et al., 2023).

Conjunctive Water Management (CWM) is one aspect of Integrated Water Resources Management (IWRM) and it is a critical component of water planning (Zhang, 2015; Van der Gun, 2020). It becomes more vital to discover a strategy for sustainable groundwater and surface water management (Gupta et al., 2013). Hence, CWM is necessary for translating into practices at a multi-level of governance (Gupta et al., 2013; Scanlon et al., 2023). Since most nations have a legacy of dealing with groundwater and surface water independently with little cooperation (Van der Gun, 2020), CWM should be concerned especially by policymakers, practitioners, water managers, and water stakeholders to understand the context of water linkage and how to manage it in one single resource for effective water planning (Van Steenbergen et al., 2015; Zhang, 2015; Safavi et al., 2016; Cobourn et al., 2017; Van der Gun, 2020).

Sustainable Development Goals (SDGs) are the global framework to support economic development, social aspects, and environmental sustainability (United Nations, 2019; Fonseca et al., 2020). Water is the one of challenges targeted by SDG6 (clean water and sanitation) (United Nations, 2019). It is evident that IWRM implementation (target 6.5) is the critical target that CWM can address directly (Smith & Clausen, 2018). Further, CWM can contribute to other targets since this approach can increase water availability and ensure the sustainability of water resources (Van der Gun, 2020). However, SDGs cannot be effectively addressed albeit CWM is still fragmented plans (Pandey et al., 2023).

This review paper aims to discuss the roles of CWM response to water security, how it is an important approach, surface and groundwater dilemmas, good water governance, water users: key actors through the CWM approach, how CWM contributed to SDGs and the ways forward of CWM expanded to transboundary conjunctive water management. This review will be useful for many countries where the demand for water is increasing while climate change and anthropogenic pressure are on the limit of water supply. Governments, policymakers, policy practitioners, local governments, water stakeholders, and end users can adapt the empirical evidence worldwide for their countries to develop the conjunctive water management framework at multiple scales of governance to expand the transboundary conjunctive water management in multiple countries.

Conjunctive Water Management: The effective approach to ensure water security

"Conjunctive water management is the management of hydraulically connected surface water and groundwater resources in a coordinated way, such that the total benefits of integrated management exceed the sum of the benefits that would result from independent management of the surface water and groundwater components"

Sahuquillo and Lluria, (2003)

The CWM definition highlights the connectivity of surface and groundwater resources; yet, it is still vague to understand the CWM approach and how to practice it. Recently, several researchers have attempted to clarify the concept between conjunctive water use and conjunctive water management (see, Foster et al., 2010; Bejranonda et al., 2013; Sing, 2014; Lautze et al., 2018; Van der Gun, 2020; Sabale et al., 2023). Conjunctive water use refers to the uses of SF, GW, and any other components to ensure water availability (Lautze et al., 2018; Van der Gun, 2020; Sabale et al., 2023). However, conjunctive water management represents the integration of management (i.e. monitoring and coordination) between surface water and groundwater to balance the water supply and water demand in optimum use, equity, and environmental sustainability (Bejranonda et al., 2013; Lautze et al., 2018; Sabale et al., 2023). For the explicit understanding of CWM, the principles have been identified (Fullagar, 2004).

- *"Where physically connected, surface water (including overland flows) and groundwater should be managed as one resource."*
- *"Water management regimes should assume connectivity between surface water (including overland flows) and groundwater unless proven otherwise."*
- *"Water users (groundwater and surface water) should be treated equally."*
- *"Jurisdictional boundaries should not prevent management actions."*

These principles have become the challenges of CWM due to the difficulties of GW monitoring and volumetric use measuring, traditionally separated surface water and GW management, lack of knowledge and information related to the impact of GW extraction on SF water, and CWM assessment framework are not widely developed and practised (Safavi et al., 2016; Ross, 2018; Pandey et al., 2023). However, these challenges should be a concern for multi-actors in the water sector to coordinate and trade-off CWM issues (Safavi et al., 2016). These actions need to be urgently called for active cooperation to cope with the uncertainty of climate, environment, and anthropogenic impacts on the security of water resources (Van Steenbergen et al., 2015; Van der Gun, 2020; Sabale et al., 2023).

However, several scholars have attempted to explore the states of CWM to understand the multiple contexts and their challenges. CWM under climate change is reviewed by Zhang (2015) and Sabale et al. (2023). Climate change has impacts on surface water and groundwater supply. Changes in precipitation and temperatures limited water availability. Thus, CWM should be concerned with the climatic factors to transcend to effective CWM under the climate change scenario (Zhang, 2015). Further, the hydrologic linkage between SF and GW is explored by Evans et al. (2018). They highlighted that both water resources should be managed in one single resource due to the close connection of hydro characteristics and their impacts on each other.

Regarding the policies and strategic aspects, Mattiuzi et al. (2019) reassessed water allocation strategies in southern Brazil. It is evident that CWM plays a key role in reducing water scarcity and water management costs. This approach can be developed for effective strategies to allocate water resources for sustainable irrigated agriculture. Meanwhile, Portoghese et al. (2021) found that unfair SF water pricing strategies have negative impacts on GW resources due to GW being more abstracted than SF water. Thus, water strategies should consider the other water source impacts by using CWM. However, Zhai et al. (2022) reveal regional water shortage can be improved by the efficiency of surface-water transport and appropriate GW use in the case of the Amu Darya River Basin, Central Asia. These are the empirical evidence related to CWM which needs to be applied to water management.

To overcome global water challenges, it is required to coordinate and develop conjunctive solutions to sustainable water management (Cosgrove & Loucks, 2015; Van Steenbergen et al., 2015; Van der Gun, 2020; Sabale et al., 2023). Sustainable water management frameworks and mechanisms should be put in place to enable conjunctive use and contribute to improving water security (Marques et al., 2022). Nevertheless, the barriers to CWM implementation are elicited. Importantly, the traditional institutional arrangement of SF & GW management is the root problem of water management. It has led to a lack of communication and collaboration across water sectors. Consequently, CWM is the floated plan in many developing countries. Besides, sustainable extraction of SF and GW are estimated separately resulting in inadequate information on total water availability. This limitation led to uncontrollable water demand. Likewise, a lack of investment in technological development is a constraint to transforming to CWM as well (Brodie et al., 2007; Ross, 2018; Nicollier et al., 2022).

The significance of the CWM approach

The CWM approach is increasingly interesting for the new paradigm of water resource management over the last decades (Sabale et al., 2023). Paradoxically, this approach is inherent in disorganization and frequently overlooked in water management. Nevertheless, the advantages of CWM are investigated and confirmed by numerous scholars. First, CWM ensures water security and resilience (Safavi et al., 2016; Ross, 2018; Iwanaga et al., 2020; Van der Gun, 2020; Mishra et al., 2021; Cruz-Ayala & Megdal, 2022; Marques et al., 2022; Ndeketeya & Dundu, 2022; Sabale et al., 2023; Scanlon et al., 2023). The empirical shreds of evidence are presented through the case studies. The potential benefits of

CWM are shown as outcome improvement under dry conditions since groundwater is developed for ensuring water security (Iwanaga et al., 2020). Further, Managed Aquifer Recharge (MAR) is represented as a significant tool of CWM to increase groundwater supply to improve water security and resilience in the dry season (Cruz-Ayala & Megdal, 2022; Sabale et al., 2023). Thus, CWM is thus the solution to improving water security for climate change adaptation (Ndeketeya & Dundu, 2022; Sabale et al., 2023).

Second, CWM supports the environment and ecosystem sustainability i.e. flood control, water pollution reduction, salinity control, ecosystem conservation, etc. (Wu et al., 2016; Song et al., 2020; Van der Gun, 2020; Sabale et al., 2023). Flood control is mitigated by MAR which is the key tool of CWM. MAR is used to allocate flood water into the aquifer to infiltrate the GW supply. Meanwhile, the threats from water pollution in surface water will be mitigated by shifting the SF supply to the GW supply. Regarding the key evidence of salinity control, Daneshmand et al. (2014) emphasize that conjunctive water use reduces salinity by 50 % in the wetland of the Zayandehrood water basin. Further, the ecosystem will be conserved if CWM is implemented. Due to the linkage between SF and GW supply, CWM can estimate the optimal use of water to balance the water for ecosystem services i.e. wetland, oasis, aquatic ecosystem, etc. These are significant to concern the roles of CWM in ecosystem sustainability.

Third, CWM contributes to socioeconomic stabilities and sustainable livelihood (Van der Gun, 2020; Sabale et al., 2023). Daneshmand et al. (2014) confirmed the role of CWM in positive socio-economic development through the application of an integrated water quantity-quality optimization model. The results show the potential of water supply in socio-economic development since conjunctive water use can improve water quality. In the case of supporting agricultural development, Vanderzalm et al. (2022) highlighted the potential tool of CWM called MAR which is a low-cost strategy to ensure water security for supporting effective agricultural water management. Currently, the evidence of socio-economic contributions from CWM is revealed by Jain et al. (2023). They proposed the optimization model of water allocation for crop production. This model can increase the crop net return and balance conjunctive water use. The model implied socio-economic management and sustained water supply.

Fourth, CWM reduces planning flaws. The constraints of separated water management are the overlap planned and the over budgets. Water can be managed effectively if it is accounted for as a single resource. The replicated water plans will be reconsidered for the new plan for holistic water management. Surface and Groundwater availability can be avoided the double counting. The reduction of the planning flaws can decrease the overlap budget for both water resource development (Van der Gun, 2020; Sabale et al., 2023). Eventually, CWM can pave the way toward effective transboundary water management (Wada & Heinrich, 2013; Lautze et al., 2018; Van der Gun, 2020; Dodo et al., 2022; Sabale et al., 2023). However, Lautze et al. (2018) revealed that the global transboundary water treaties are very little in conjunctive water management. Hence, they recommended that it is necessary to outline practical paths toward the actual application of conjunctive water management in a transboundary context.

Further, water conflict resolutions can be solved by CWM. Banadkooki et al. (2022) proposed an integrated model for optimal water allocation in conjunctive water management to resolve water conflicts in arid areas. It will be able to protect aquifers while meeting water demands by incorporating demand management, wastewater treatment, and the absence of industrial development in development scenarios. On the other hand, this water allocation model may not be appropriate for industrialized countries due to the scenario being set to non-existent industrial development. It may imply that industrial zoning should be implemented and determine this area to be a non-industrial zone to apply this model.

Groundwater and Surface water: Nested to a single resource

Water resources have been separately managed for a long time (Ivkovic et al., 2009; Ross, 2018). Many researchers in the field of water management have attempted to investigate the benefit of CWM as mentioned in the previous section. Many of them confirmed the role of CWM in ensuring water availability and secure livelihood in the dry season. Due to surface water insecurity, climate change is the one of driving forces affecting the surface water supply (Zhang, 2015). It is acknowledged that rainfall uncertainties or changes in rainfall patterns including higher temperatures affected the water cycles (Wang et al., 2016).

Surface water shortage is thus a critical challenge to water security, especially in the dry season (Zhang, 2015). Besides, water demand tends to increase driven by population growth, urbanization, agricultural expansion, and industrialization. These driving forces have an impact on water security in terms of inadequate water supply and water pollution. These phenomena lead to water conflicts and competition among sectors due to inequality of water allocation and access (Wu et al., 2016). Thus, CWM can be adapted to respond to water demand and maintain water resilience under climate change (Zhang, 2015; Scanlon et al., 2023).

However, many countries have attempted to extract GW resources to meet the water demand (Zhang, 2015; United Nations, 2022). Thus, GW has become a major source for several purposes worldwide. GW is extracted for socioeconomic development i.e. agriculture, industry, domestic use, etc. However, the challenge of GW management still exists since a large proportion of GW extraction is not easy to monitor while the institutional constraint is a barrier to good groundwater governance. These constraints have led to GW exploitation and emerging serious impacts such as land subsidence, GW depletion, and seawater intrusion into aquifers (Muenratch et al., 2022; United Nations, 2022; Scanlon et al., 2023).

Conversely, many researchers have explored the key role of GW and strategies for sustainable groundwater management conjunctive with surface water (Grönwall & Oduro-Kwarteng, 2018; Scanlon et al., 2023). Through several cases, Grönwall & Oduro-Kwarteng (2018) highlighted GW as a strategic resource for improved water resilience. Meanwhile, water banking in the aquifer is a tool for drought resilience in the Murray Darling Basin (Page et al., 2022). Paradoxically, the high rate of GW for irrigation has led to GW depletion. This should be recognized by the importance of CWM to ensure water sustainability through the case of the US Central Valley, the initiatives to trap flood waters for regulated aquifer recharges (Scanlon et al., 2012; 2023). Conversely, Bhat et al. (2023) have investigated the conjunctive use of canal water and groundwater based on farmers' practices in Ravangaon, Maharashtra, India. It is concluded that conjunctive use is difficult to monitor actual water use. This approach required the advancement of water strategies for sustainable CWM.

Good Water Governance: a key pillar for CWM performance

Good water governance is required to enhance water security (Babuna et al., 2023). Van der Gun, J. (2020) indicates good water governance can facilitate CWM due to the clear institutional framework, effective water policies, multiple actors' involvement, and adequate knowledge and information about CWM. These components will be the strong basement of good water governance and a key pillar for contributing to the CWM approach. Nevertheless, institutional frameworks for CWM toward transboundary CWM have still received little attention (Lautze et al., 2018).

Conjunctive use is required for practical implementations to ensure water security at multiple scales (Das, 2023). However, Du et al. (2022) evaluated distributed policies for conjunctive surface water-groundwater management in large river basins. The findings implied the requirement for effective policy design to cover spatiotemporal variations in the physical hydrological system to ensure water security over space and time. Thus, multi-level water governance is essential to unpack the specific water issues according to the spatial context.

However, customary rules or informal institutions of water management are significant at the local scale (Gudaga et al., 2018; Gilmore et al., 2022). Gilmore et al. (2022) emphasized the importance of informal institutions nested with formal institutions by using the concept of water governance. Decentralized water management is promoted through the local self-organization of water management nested with the role of the central government. The nested water institution provides the practical framework to facilitate local water management to enhance the institutional capacity and cope with water challenges in semi-arid regions. However, combining economic and sectoral strategies i.e. investment in agricultural water consumption to supply water for socioeconomic growth and ecological demands. This strategy would give prospects for sustainable development in the river basin (Daneshmand et al., 2014).

In India, the need for groundwater governance is currently called for action due to GW is a key water resource (Das, 2023). Good GWG can enhance the performance to expand transboundary groundwater security (Albrecht et al., 2017). Thus, GWG should be strengthened to scale up groundwater management in multiple countries. These are the signs of literature that paved the way toward good water governance and contributed to transboundary CWM collaboration.

CWM contributed to Sustainable Development Goals

Sustainable Development Goals (SDGs) are widely recognized in the global development framework that developed and developing countries must address. The 17 goals and their targets are necessary to be addressed to overcome the challenges of sustainable development by 2030 (United Nations, 2019). However, clean water and sanitation (SDG6) is the major goal related to water security worldwide (United Nations, 2018). Many countries have faced the constraints of water availability and scarcity, especially in arid and semi-arid regions (Rosa et al., 2020; He et al., 2021). Thus, CWM is the one approach that effectively responds to SDG6 by increasing the water supply and ensuring water security for sustainable water management (Van der Gun, 2020).

Globally, the evidence of CWM and SDGs is very little. Nevertheless, Bhaduri et al. (2016) confirmed the role of water in achieving Sustainable Development Goals. Empirical findings highlighted the value of CWM in the SDG framework. Water should be conjunctively managed to ensure water security for socio-economic development and response to the SDGs (Marques et al., 2022). Thus, SDG 6 – clean water and sanitation is the major goal for CWM adoption to increase water supply and meet water security (Shrestha et al., 2021).

Global water security is a critical challenge to sustainable development (Frone & Frone, 2015; Mishra et al., 2021). Since water plays a key role in socio-economic development and balancing the ecosystem, water resources should be sustainably consumed and managed (United Nations, 2018). However, CWM contributes to the SDGs especially SDG6 - clean water and sanitation. Target 6.5 - Implement integrated water resource management (IWRM) at all levels by 2030, including transboundary cooperation where needed. As CWM is one aspect of IWRM, water is targeted to be conjunctively managed. Further, several goals of SDGs will be ensured by CWM; no poverty (SDG1), Zero hunger (SDG2), Good health and well-being (SDG3), and Energy Security (SDG7), Climate Action (SDG 13), and Life on Land (SDG 15). To support water security under sustainable development, CWM response to SDGs is required to be archived as shown in Table 1 (United Nations, 2018; UNESCO and UNESCO i-WSSM., 2019; Van der Gun, 2020; Irannezhad et al., 2022).

Table 1 SDGs and CWM contribution

SDGs goals	CWM respond to SDGs
SDG 1 – No Poverty	Income increases due to adequate water for economic activities
SDG 2 – Zero hunger	Food and water security
SDG 3 – Good health and well-being	Adequate clean water and good sanitation
SDG 4 – Quality Education	Fresh drinking water for schools
SDG 6 – Clean water and sanitation	Optimized water uses and ensured sustainable water withdrawals
SDG 7 – Affordable and Clean Energy	Solar pumping for groundwater supply
SDG 8 – Decent work and economic growth	CWM supports economic activities (agriculture, industry, tourism, etc.)
SDG 9 – Industry, Innovation and Infrastructure	Optimized water uses in industry and water treatment
SDG 10 – Reduced inequality	Water for all people
SDG 11 – Sustainable Cities and Communities	Increase urban water supply /rural water supply
SDG 12 – Responsible consumption and production	Water saving practices
SDG 13 – Climate action	Ensure water security in the dry season
SDG 14 – Life below water	Reduced GW pollution and contamination Reduce seawater intrusion into the aquifer
SDG 15 – Life on Land	Reduce soil salination
SDG 16 – Peace, Justice, and strong institutions	Reduce water user conflicts and competition
	Support consensus among water stakeholders
SDG 17 – Partnerships for the Goals	Conjunctive water management networks

The ways forward for CWM to ensure water security toward SDG6

In the last two decades, numerous studies presented the CWM simulation-optimization models to ensure water security and pave the pathway for sustainable water management (see, Schoups et al., 2006; Hanson et al., 2010; Singh, 2014b; Safavi et al., 2016; Ashu & Lee, 2021; Hao et al., 2022; Yao et al., 2022; Gobezie et al., 2023; Jain et al., 2023; Mousavizadeh et al., 2023; Sabale et al., 2023). Further, the integrated tools and strategies for CWM were investigated. It is evident that Manage Aquifer Recharge (MAR) has become an effective tool for CWM implementation worldwide (Evans et al., 2018; Page et al., 2018; Van der Gun, 2020; Vanderzalm et al. 2022; Sabale et al., 2023; Scanlon et al., 2023; Sherif et al., 2023). Through the global advances of CWM tools and strategies, the empirical evidence is presented; (i) Distributed Pumping and Recharge (DPR), Ganges Water Machine (GWM), Pumping Along Canals (PAC) in the Ganges basin in India, Nepal, Tibet, and Bangladesh (Khan et al., 2014) (ii) the construction of on-farm irrigation reservoirs in eastern Arkansas, U.S.A. (Yaeger et al., 2018), (iii) the potential of a small dam is investigated to support CWM in North Portugal (Soares et al., 2019), and (iv) planning methods for conjunctive use in urban water supply in Yangon City, Myanmar (Hashimoto et al., 2022).

Existing literature sheds light on global knowledge of advanced CWM models and integrated tools. However, it is necessary to investigate more aspects to support CWM effectively and facilitate CWM implementation in the specific context. It is evident that the institutional and legal scope and assessment framework for CWM is little studied (see, Raines, 1996; Foley-Gannon, 1999; Blomquist et al., 2001; Ross, 2018; Pandey et al., 2023). Further, Ross (2018) found that the institutional factor is a barrier to CWM implementation. Restructuring institutional arrangements in the transition to CWM is thus significant to reduce such barriers. Additionally, CWM linkages to SDGs are not widely investigated (see, Van der Gun, 2020). To overcome the challenges, future research should elaborate on the governance aspects of CWM and expand to the contribution to SDGs including transboundary CWM to enhance the collaboration of international water management. Future research should explore this scope to address the knowledge gaps and extent of the global framework of CWM. A lot of research is related to the CWM modelling approach (see, Soleimani et al., 2021), yet, it lacks practical application to the real world. Thus, the CWM models should be practised at multiple levels to understand the pros and cons of improving the future CWM (Van der Gun, 2020).

CWM frameworks should be developed to facilitate the tasks of CWM in multi-levels of water governance including multi-actors' involvement in CWM functioning to support the policy coherence of surface water and groundwater management (Van der Gun, 2020; United Nations, 2022). The national CWM framework and local CWM frameworks also need to be developed and practised due to the different contexts according to the spatial and temporal scale (United Nations, 2022). SDG6 is required to address the water challenges by 2030. It is urgent to improve the state of CWM to respond to the targets of SDG6 (Figure 1). It is possible that the co-developing CWM framework response to the SDGs can overcome water security worldwide (United Nations, 2018; Van der Gun, 2020).

Discussion

1. The key problems in the CWM application

The key problem of CWM practices is the lack of governance provisions to facilitate CWM implementation worldwide. Lack of water data and information shared in the communities is the key challenge of CWM implementation. It is evident that limited water data were shared among water users. This is a barrier to CWM implementation at the field level since the availability of water is not known (Van der Gun, 2020). Institutional constraints, environmental concerns, economic considerations, and the political climate are the main problems behind the successful CWM implementation (Dudley and Fulton, 2006; Van der Gun, 2020; Ross, 2018). Further, GW users' conflicts are the problem while the CWM operation is implemented. Since the aquifer recharge period increased the GW level higher than normal, it caused other GW users in the same basin affected by the fluctuation of the GW level (Dudley and Fulton, 2006). These problems should be considered in future scenarios to cope with the multiple challenges of CWM practices.

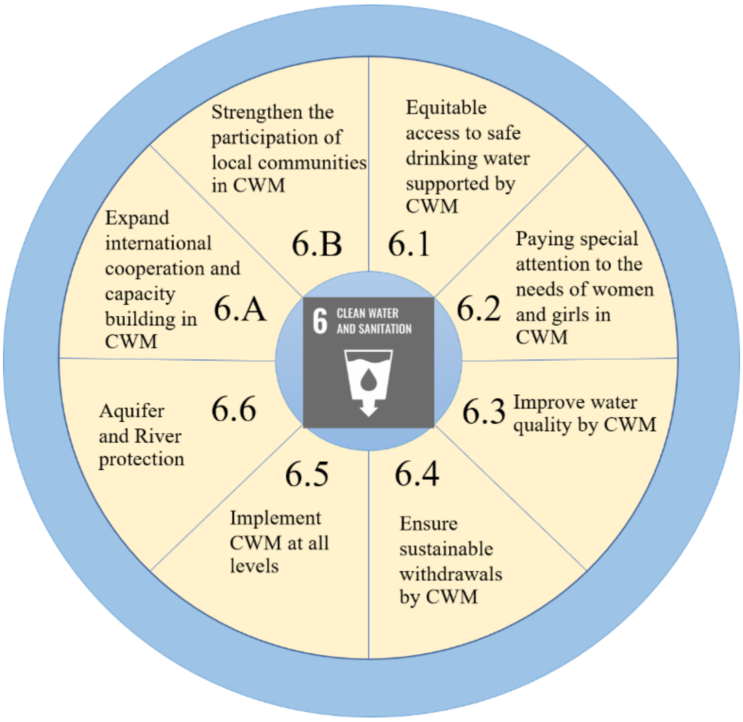

Figure 1 The ways forward of CWM to ensure water security response to SDG6

(**Source:** Muenratch, 2023)

2. The key challenges of CWM to achieve the SDG goals

The key challenge in using CWM to achieve the SDG goals is the lack of developing CWM framework connecting to SDGs to understand the appropriate indicators for the CWM assessment framework. Although Bhaduri et al. (2016) highlighted the significance of water resources contributing to SDGs, few studies have explored it. Though Van der Gun (2020) has attempted to explain the role of the CWM in contributing to SDGs, there is still less discussion on SDG indicators and how the CWM can contribute to the targets. Further, SDG6 (clean water and sanitation) is the only key target which several scholars keep priority (Shrestha et al., 2021; Van der Gun, 2020). However, SDG13 (Climate action) is a significant contribution by CWM. Climate change has affected the water cycle and drought risks. CWM can ensure the water supply to mitigate the uncertainties of the climate situation (Zhai et al., 2022). These knowledge gaps are the key challenges to exploring the appropriate CWM framework linkage to multiple SDG targets.

3. The lessons learnt from CWM practices

The key lesson learned from CWM practices paves the way forward in water security worldwide. In Nebraska, U.S.A., it is evident that CWM has been effectively implemented in this area. CWM has supported the reliable water supply and economic development. However, it is reflected that the local actors are important to the partnership of CWM operation in terms of monitoring and tracking water resources at the local scale (Strom, 2018). In Australia, MAR is applied to ensure water supply for agricultural development. This CWM practice has highlighted the benefit of MAR in lowering the cost of agricultural production and increasing productivity. In agricultural water management, surface and subsurface aquifer storage play complementary roles (Vanderzalm et al., 2022). However, there are several tools and approaches related to CWM i.e. Conjunctive use, MAR, Watershed management, Desalination, Wastewater management and recycling, etc. (Van der Gun, 2020). These tools are necessary to widely apply to confirm the significance of CWM in water security and achieving the SDGs toward sustainable conjunctive water management.

Conclusion

Conjunctive Water Management is an effective approach to ensure water security in the contemporary world under anthropogenic and climate change impacts. Unfortunately, the key barrier to CWM implementation is traditional water management. Thus, global strategic plans for water management should be adapted to the CWM approach to effectively respond to the SDGs. Regarding the valuable contribution, CWM ensures water security, ecosystem sustainability, socioeconomic stability, sustainable livelihood, water planning flaws reduction, and paving the way toward transboundary CWM. Yet, good water governance and the role of water users are required to enhance the efficiency of CWM adoption. Consequently, CWM represents constructive approaches for strengthening sustainable water management to respond to sustainable development toward transboundary CWM in future collaboration.

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