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Towards transition pathways in agriculture and livestock in coastal areas of the Vietnamese Mekong Delta from an agricultural water management perspective

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Abstract

The Vietnamese Mekong Delta (VMD) is the main agricultural production region in Vietnam producing rice, fruits, shrimps and livestock among a variety of crops. The current VMD agricultural production system (APS) is under threat from the rise in sea level aggravated by climate change, causing further inland salinity intrusion. Transition pathways towards increased salinity adaptation in APSs are therefore required to maintain food security, in particular in coastal zones. This study assesses the present water sources usage for APSs and associated quality, quantity and food safety issues. Water-related stresses observed by farmers in the coastal Tra Vinh region are described based on a focus group discussion and in-depth household interviews. Multiple water sources were described for agricultural practices (e.g. surface water, deep well, rainwater) which differed per season. Also, farmers reported to be affected by salinity (67.3%) and groundwater shortages (28.8%) hampering current agricultural production. Currently, farmers affected by water stress reported to change the cropping calendar or cultivation practices. Some farmers did not grow crops due to water stress and were looking for new jobs and new places to live instead. Subsequently, transition pathways focusing on salinity adaptation to maintain food security and sustainable livelihood are proposed. From a water and soil management perspective these include: (i) freshwater storage and treatment; (ii) irrigation innovations to produce crops under scarcer freshwater availability, (iii) in situ water treatment to make salt/brackish water more suitable for crops freshwater storage as a buffer in dry season; and (iv) increase soil organic content which can improve soil water retention and reduce impacts of salinity on crops. It is recommended to test multiple transition pathways on farm level in representative regions in the VMD through living labs or demonstration farms.

Keywords: Mekong Delta, Water Management, Agriculture, Climate Change Adaptation, Salinity Intrusion, Water Governance

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1. Introduction on agriculture, aquaculture and livestock activities

The Vietnamese Mekong Delta (VMD) has a size of around 40,150 km^2 formed by sedimentation of silts from the Himalayan region (Hays, 2019). The area contains rich soils and has sufficient water sources particularly from the Mekong River and is therefore the main agricultural region of Vietnam in terms of productivity with 50% of the surface area under cultivation. The major crop is rice, which is grown on around 10,000 km^2 (or 50% of cultivated land). Other crops include vegetables (i.e. leafy greens, beans, tubers) and fruits (i.e. grapefruit, dragon fruit, mango, banana) with a total surface area of 1,100 km^2 and 3,600 km^2, respectively (Binh et al., 2011; Vietlinh, 2021). Besides agriculture, the region is also characterised as a main aquacultural hotspot where fish and shrimp are cultured in ponds accounting for 80% of the national production on around 3,800 km^2 of land (Nghiem, 2010). Especially shrimp can be found in coastal provinces of the VMD while inland fisheries mainly consist of indigenous fish species from river-floodplain systems, rice fields and the estuary zones (Hortle, 2009). In addition, the VMD counts 581 large-scale livestock businesses (Smith, 2013) that consist mainly of beef, pork and poultry raising (Knips, 2004). Overall, in the coastal zone of the VMD, saline or brackish aquaculture is the dominant form of land-use mainly consisting of shrimp ponds. These ponds were formerly mangrove forests which have been transformed to shrimp farming culture to expand the production area. However, fruit gardens, vegetables and rice fields can be found to a lesser extent in areas under fully controlled irrigation schemes. Also, systems that are a mixture between rice or other crops (in the rainy season) and shrimp cultivation is practiced (Dang, 2020) while other brackish or saline farming systems are applied such as crab and several fin-fish species as well (Wilder & Phuong, 2002).

The population of VMD counts 16 million (General Statistics Office [GSO], 2021) and most of them are involved in agriculture- and aquaculture-related activities. Rice, fruits and vegetables are mostly farmed by smallholder farmers who are embedded in markets and contract farming. In addition, these farmers grow vegetables and raise cattle for own production. External inputs such as fertilisers and agrochemicals are applied, although extensively. Following the food system typologies by Marshall et al. (2021), the following typologies can be identified in coastal VMD: most farmers can be characterised as being part of rural and traditional to emerging and diversifying food systems as farmers within this system produce both for self-consumption and for (internal) markets with modest external inputs. However, some farmers specifically produce for the export market (e.g. Pangasius, fruits) and can be characterised as industrial and consolidated farmers. Farm sizes differ depending on produced products. In Soc Trang province, for example, the largest farms are the rice-aquaculture integrated/rotated farms (average 19,437 m^2), followed by aquaculture (average 14,547 m^2) and fruits or vegetables (average 3,841 m^2) (Hamer et al., 2020).

The current agricultural and livestock systems (meat and associated products and fish) are under threat from salinity intrusion from estuaries due to sea level rise and reduced flows from the Mekong River. As such, freshwater availability for crop irrigation

Table 1
Water productivity and salinity tolerance for crops and livestock

	Vegetables	Fruit Trees	Rice	Livestock
Water productivity (kg/m^3)	4.2	1.1	0.7	0.2
Salinity tolerance level (no reduction in yield mg/L)	383–1,984	448–1,344	640	2,000–4,000[a]

Production systems in the Mekong Delta of Vietnam (Sources for water productivity based on green and blue water: Mekonnen & Hoekstra [2011]; Mekonnen & Hoekstra [2012]; Pahlow [2015]. Sources for salinity tolerance for crops: New South Wales [2017]).
[a]Salinity tolerance levels of livestock are presented in mg/L for poultry and pigs, respectively (Smith, 2021).

and livestock production is negatively affected. In a response towards climate change, the Mekong Delta plans an additional 450,000 ha under fruit, vegetables and seafood production by 2030 as part of the Ministry of Agriculture and Rural Development's effort to shift the Mekong Delta towards more sustainable agriculture practices (MD-ATP, 2019). Vegetables, fruit trees and fish/shrimp provide more opportunities for effective yields under saline conditions compared to rice (see Table 1). However, transitioning the current agricultural production system only will not be sufficient to cope with climate change. To some extent, cultivation of rice and other staple crops, which have low salt resistance (see Table 1), will have to be sustained in order to maintain food security under continuously increased salinisation aggravated by climate change. Therefore, improved water and soil management practices should be applied along other measures, and this is also presented in resolution 120/NQ-CP by The Socialist Republic of Vietnam (2017).

The Deltas under Pressure (DUP) project aiming on Vietnam and Bangladesh is developed to establish guidelines for agricultural areas within both deltas to enhance salinity adaptation in coastal regions (Wageningen University & Research [WUR], 2022). The project presents multiple solutions varying from interventions in livestock systems, construction of mangrove forest, application of salt resilient crops and species, or water treatment among others. This article specifically focuses on possible transition pathways on farmer field level from a water and soil management perspective in coastal VMD. The aim of this article is to identify (i) the current water sources used for agriculture, aquaculture and livestock in coastal zones of the VMD; (ii) associated quality and quantity issues of those water sources; (iii) impact of identified water issues on food safety; (iv) current farmer experiences and responses to water-related stresses; and (v) identification of water- and soil-related transition pathway options to enhance resilience towards water-related stresses in coastal VMD.

2. Materials and methods

Literature review was conducted to assess the usage of different water sources in agriculture, aquaculture and livestock sectors as well as to identify the water quality and quantity issues of those water sources and food safety issues associated with water. A review of research literature was carried out that explored peer-reviewed articles, policy documents and investment planning documents pertaining to the 2010 to 2022 period. Furthermore, the review was verified and enriched by experts from the agricultural and water management department of Can Tho University.

A Focus Group Discussion (FGD) with 100 farmers in Cau Ngang and Tra Cu districts in the coastal Tra Vinh region was conducted which entailed questions regarding experienced pressures on agricultural-aquacultural and livestock farming from water stresses. Farmers were asked to give a score for the experienced pressures varying from 1 (low value/priority) to 9 (high value/priority). Farmers were also asked what they perceive as promising options to deal with water stresses. In addition, 52 in-depth household interviews were conducted within the same districts to reveal more detailed information regarding water sources usage for rice, vegetables, livestock and aquaculture for both wet and dry seasons. The household interviews also identified whether farmers experienced groundwater, salinity and drought stress during the year and which adaptive measures were taken (if any).

3. Results

The Mekong Delta has an abundance of water sources available for agriculture, aquaculture and livestock rearing, although availability varies between seasons and zones. In the rainy season (June to November), the upper Delta is largely inundated, while in the dry season (December to May) the lower delta is affected by seawater intrusion and drought stress. Water quality is an issue within certain regions and a risk with respect to agriculture, aquaculture and livestock rearing and food safety. A detailed overview is presented in this section.

3.1 Water Source Usage in Agriculture, Livestock and Aquaculture

Data obtained from the household survey conducted during this study showed that for various purposes (living, rice or vegetable cultivation, shrimp and livestock) different water resources are applied during the dry season and rainy season (i.e. rain-fed, canal, pond, dug well, deep well, tap water, bottled water) (see Figure 1). Based on the survey, the main primary water resources applied for living during the dry season are rain-fed (36.5%), deep well (32.7%), tap water (26.9%) and dug well (3.9%), while during the rainy season the primary water resources reported to be utilised are rain-fed (55.8%), followed by tap water (25%) and deep well (19.2%). For rice cultivation during the dry season, the primary water resource is canal (83.3%) followed by deep well (11.1%) and rain-fed (5.6%) (n = 18), while during the rainy season this is reported to be rain-fed (74.3%) followed by canal (25.7%) (n = 35). For cultivation of vegetables, mainly water from the deep well seems to be applied during the dry season (100%; n = 13), while during the rainy season this is especially rain-fed (90.9%) followed by deep well (9.1%) (n = 11).

Figure 1. Overview of the water resources that are mentioned by farmers for living, rice production, vegetable production, shrimp production and livestock as reported in the in-depth household interviews (n = 52) during the dry and rainy seasons. Depending on what the water is used for, the first four water resources are reported, and the number of households using that water resource is expressed relatively to the number of entries (n) for that matter in percentage (y-axis).

For shrimps during the dry season, canal water is applied (100%; n = 6), while during the rainy season both canal (50%) and rain-fed (50%) are reported to be used (n = 6). For livestock during the dry season, the primary water sources reported are deep well (68.6%), rain-fed (11.4%), dug well (8.6%), tap water (8.6) and bottle (2.9%) (n = 35), while during the rainy season this changes slightly to deep well (67.7%), rain-fed (14.7%), dug well (8.8%), tap water (5.9%) and bottle (2.9%) (n = 34). These findings are in line with another study in the Vietnamese coastal zone of the Mekong Delta which assessed the water sources used for shrimp and crop cultivation. This study found that groundwater (50%), rainwater (31%), surface water (13%) and seawater (6%) were the water sources applied. In case crops are grown, they are watered twice daily (63%) or twice or thrice (19%) in the dry season. In the wet season, irrigation is less than daily (37%) or once per day (30%) or every two days (22%) (Hamer et al., 2020). The study of Hamer et al. (2020) shows a large dependency on groundwater sources for crop irrigation as well as for shrimp cultivation systems to maintain optimal salinity levels in the ponds. For this water resource usage, groundwater is extracted from the lower Pleistocene layer (123–158 m) by 57% of the farmers, while 30% extract groundwater from the middle Pleistocene layer which is situated 65.7 to 117.8 m below surface level (Hamer et al., 2020). Besides the large groundwater abstraction for agriculture and aquaculture, the coastal regions such as Soc Trang province are simultaneously experiencing land subsidence, reduced freshwater flows from rivers and sea level rise (Bosma et al., 2016). As such, it is expected that there will be main pressure and risk in maintaining fresh groundwater resources in the future.

3.2 Natural Water Sources' Quality and Quantity Issues in the Mekong Delta

3.2.1 Rainwater The VMD is characterised as a tropical monsoon region with annual mean rainfall between 1,750 and 2,500 mm per year. As a result of climate change, this is expected to increase with 13.5% in the next 20 to 30 years (Mekong River Commission [MRC], 2021). This rainfall is mainly occurring in the wet season, although climate change causes shifts in rainfall patterns from less rainfall in the early wet season to increased rainfall towards the end (Sebastian et al., 2016). Shifting rainfall patterns is an important aspect in the context of agricultural, aquaculture and livestock production. The quality of rainwater is generally sufficient when compared to WHO and Vietnamese drinking-water guidelines. However, when harvested rainwater is collected from metal roofs it is frequently (around 8%) contaminated with lead. Coliforms in harvested rainwater are regularly present and are caused by bird droppings on roofs and/or insufficient coverage at storage basin which allows for pathogen contamination of stored water (Wilbers et al., 2013). Although rainwater is a potable water source suitable for livestock rearing, sufficient storage capacity and measures (e.g. low-cost water treatment units) to keep water at good quality is therefore required, especially for family usage during the dry season. Storage of rainwater for irrigation is not viewed as a feasible solution due to limited space for storage.

3.2.2 Surface Water The Mekong Delta of Vietnam is characterised by its dense network of canals and rivers which comprise around 25,000 km (DLR, 2018). The channel system in the VMD is fully interconnected, without separation between irrigation channels and drainage canals. There are different types of canals varying from main canals which are 70–100 m in width and 3–5 m in depth to secondary channels, which are 30–50 m in width and 2–3 m in depth. Large parts of the VMD are controlled by sluice gates and pumps, which are managed by local authorities (Le et al., 2023). In addition there are many primary canals which are used for irrigation and drainage from agricultural fields with low flow velocities. Canal flow differs significantly between seasons with 75% of annual water flow occurring during the rainy season (Ruiz-Barradas & Nigam, 2018). During the rainy season, 35% to 50% of the total surface area of VMD is annually flooded, particularly in the upstream regions (MRC, 2005). This is a main reason for farmers to apply mixed systems in areas where flooding occurs, consisting of agriculture in the dry season and fish/shrimp cultivation during the rainy season. Climate change is expected to cause more extreme floods and river flows, although the flood peak time is not expected to vary significantly (Try et al., 2020).

Surface water in the Mekong Delta is polluted with *E.coli* and other coliforms at all locations while other pollutants like heavy metals are often below WHO and Vietnamese drinking-water guidelines (Wilbers et al., 2014). However, in acid sulphate soils, the leachate water contains increased concentrations of aluminium which affects the growth of crops particularly in the dry season (Minh et al., 1997). Surface water is also polluted with (agro)chemicals (Chau et al., 2015) caused by pesticide use in agriculture and aquaculture mostly but also from industrial effluents. Another point of concern from a water quality perspective is the concentrations of salts in surface water. As the Mekong Delta is a low region with elevations between 0 and 5 m (with most of the delta <2 m), it is extremely vulnerable towards sea water intrusion caused by sea level rise particularly in the dry seasons. A study by Loc et al. (2021) clearly shows higher salinity levels in water over time and that levels are moving inland (Figure 2), causing severe pressure on agriculture, aquaculture and livestock rearing activities in the region (Mekong Delta Plan, 2017).

3.2.3 Groundwater The subsurface structure and hydrogeological units in the Mekong Delta are classified according to geological formations: Holocene, Pleistocene, Pliocene and Miocene aquifer systems (Wagner et al., 2012) and are located below ground level around 0 to 49 m, 31 to 193 m, 153 to 381 m and 275 to 550 m, respectively (Duy et al., 2021). Farmers using groundwater wells report well depths varying between 30 and 130 m below surface level, thus from Holocene and Pleistocene sources (Wilbers, 2014). Due to over-extraction of groundwater for crop irrigation, shrimp and fish cultivation, drinking-water supply, and industrial purposes, these levels are dropping, and Duy et al. (2021) found decreases in groundwater level trends between 0.01 and 0.55 meters per year depending on location and aquifer (see Figure 3).

The lowest decrease is observed in the shallow aquifers, which is caused by annual replenishment from surface water sources (Wagner et al., 2012). Moreover, seasonal fluctuation

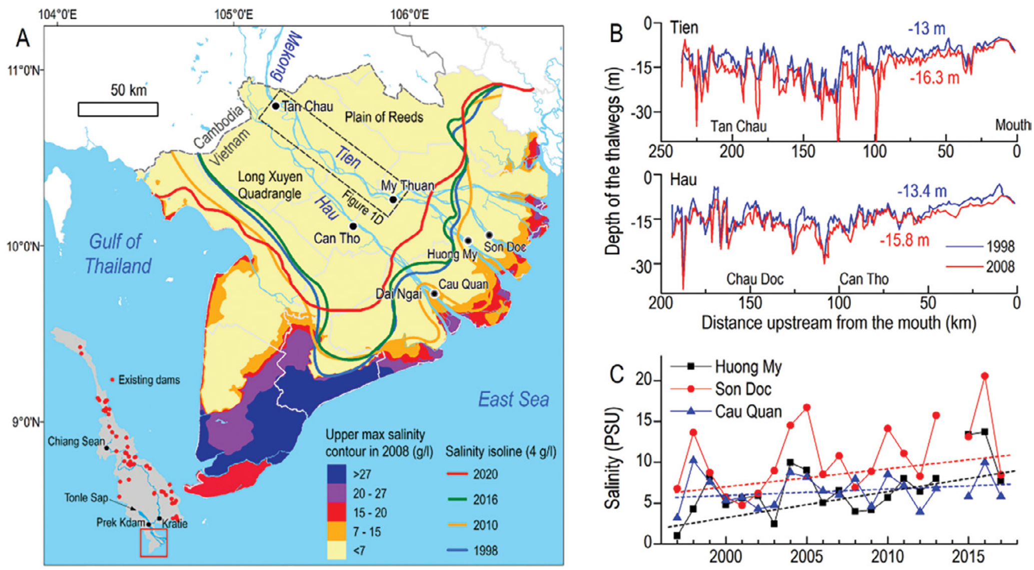

Figure 2. Salinity intrusion over the period 1998 to 2020 during dry seasons (Source Loc et al., 2021).

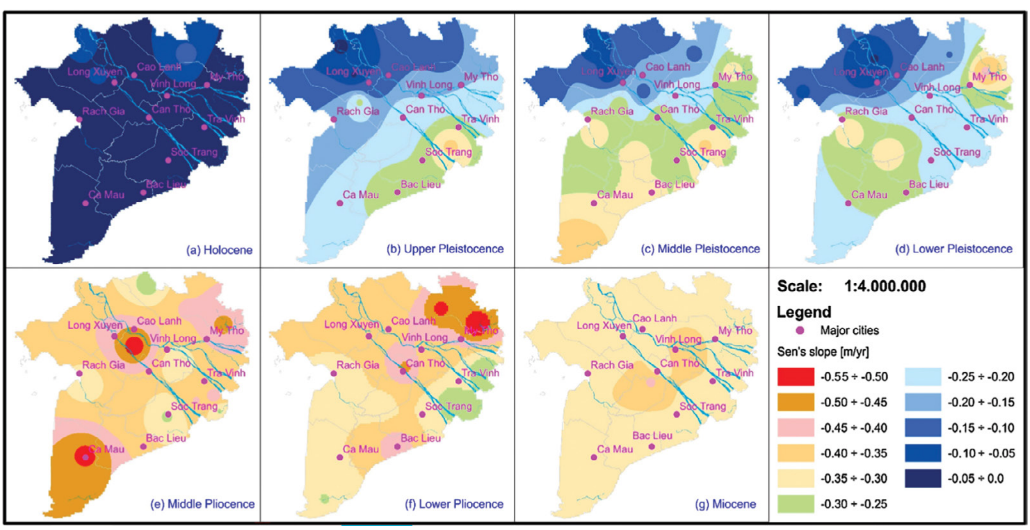

Figure 3. Annual groundwater level decrease in the Mekong Delta (Source: Duy et al., 2021).

of around 2 m in the shallow groundwater aquifers shows the direct connection between surface water and groundwater (Duy et al., 2021). The deeper groundwater layers are less replenished by surface water sources and thus drop faster compared to the shallow aquifers.

The groundwater quality severely fluctuates depending on location and aquifer used. At some locations it is of sufficient quality for irrigation and drinking, while at other locations the salinity content is too high. Many wells contain *E. coli* and other coliforms. Rising salt concentrations in groundwater above drinking-water level are locally observed, and highest values are mostly observed in regions where farmers apply deeper groundwater wells of $>$100 m below surface level (Wilbers, 2014). The reasons for the local rising salinity levels in groundwater may be caused by overexploitation, relative sea level rise, storm surge, changing precipitation and temperature regimes, uncontrolled drainage canals, operation of hydropower dams, and rapid development of aquaculture, although more research on causes is required (Xiao et al., 2021). Further groundwater quality issues include iron concentrations, which are generally above WHO and Vietnamese drinking-water quality standards (Wilbers, 2014), which may be harmful to sensitive irrigation equipment.

3.3 Impacts of Water-related Stresses on Food Safety

Access to safe water is essential for human health, not only in terms of drinking water but also for food preparation and personal hygiene. Microbiological and chemical hazards present in the water source can not only affect human (or animal) health directly via drinking water but can also have an impact on food safety due to transfer and possibly the accumulation of microbiological or chemical hazards in edible food products during, for example, food production and food preparation. How a water source is applied, for example, as drinking water, for irrigation purposes, for other agricultural production systems (e.g. livestock) or for food preparation, influences the possible impact on food safety as well.

As derived from the household interviews, different water resources were reported to be used for different agricultural production systems. Surface water, deep well and rainwater (during the rainy season) were the major water resources reported to be applied. As reported in the WHO Guidelines for drinking-water quality (World Health Organization [WHO], 2011), which provides a scientific supported point of departure for development of national guidelines for drinking-water quality, each of the aforementioned water resources are associated with different possible chemical and microbiological hazards. As such, surface water generally needs to be disinfected and often also filtration to ensure microbial safety (WHO, 2011). Chemical contaminants can also be present, which will depend on the location and can range from, for example, pollutants, agrochemicals or heavy metals. Deep well water can possibly be contaminated with naturally occurring elements in high levels (e.g. lead, arsenic), depending on the depth and location of the well, or with other contaminants due to, for example, leakage from the surface environment. Rainwater is, compared to the other water resources, relatively absent of chemical and microbial hazards initially. However, rainwater harvesting and collection systems can introduce impurities/contamination sources; due to that it can dissolve, for example, metals and other impurities from applied materials (e.g. lead) or result in increased coliform formations (WHO, 2011). When contaminated water is applied in, for example, rice or vegetable cultivation, this can result in possible transfer contaminants to the edible parts of the crops, which, depending on the type of chemical and amount of dietary exposure, can affect human health

(Al-Farsi et al., 2017; Hua et al., 2022; Khan et al., 2015). Thus, it is evident that when food system transitions are set in place because of the reported salinity issues and the water resources change, the potential impact on food safety needs to be considered.

3.4 Farmer Perceptions and Responses Towards Water-related Stresses

Results from the FGD revealed that farmers in the Cau Ngang and Tra Cu districts are experiencing various water-related stresses affecting their income and agricultural activities, mainly as a result of rising salinity content in water and growing groundwater shortages.

Of the farmers who took part in the household interview, overall, 67.3% reported to be affected with salinity, for an average period of 3.7 ± 1.5 months throughout the November-June period. Possible solutions reported were (i) dropping season, (ii) controlling the sluice gate and (iii) pumping freshwater and adjustment of the growing calendar. Issues with groundwater were reported by 15 out of the 52 total household entries (28.8%), for an average period of 6.9 ± 3.7 months throughout the year. A shortage of groundwater was reported by 12 out of the 52 total household entries (23.1%), for an average period of 2.3 ± 0.5 months throughout the January-May period. Possible solutions reported were (i) dropping season, (ii) improving the capacity of groundwater, (iii) using tap water and (iv) selection of new varieties that can tolerate drought stress.

Looking at rice farmers specifically (35 out of 52 households), 79.4% indicated to be affected by salinity for an average period of 3.4 ± 1.4 months during the November-June period. Multiple options were mentioned as adaptive measures to be taken. For example, the usage of groundwater as alternative water source instead of surface water was mentioned, while controlling the sluice gate, adjustment of the growing calendar and dropping season were mentioned as well. Besides salinity, issues with groundwater have also been mentioned which also resulted in 32.4% of those farmers who reported to be affected by groundwater issues for an average of 6.7 ± 3.5 months throughout the whole year, and 36.5% seem to be affected by a shortage of groundwater for an average period of 2.4 ± 0.5 months during the January-May period.

Livestock was indicated as the major labour activity for four households and included cows, goats and/or poultry. As much as 50% of those households reported to be affected by salinity during the January-May period. Issues with groundwater were reported as well during the March-April period.

Vegetable/crop was indicated as major activity for two households only. One of those has a farming system involving rice and vegetable production, and one has a farming system focusing on weed. Both households report groundwater issues but no salinity issues.

Farmers also proposed ideas for how salinity and drought should be addressed. For salinity, development of new brackish farming practices and innovations in irrigation management and practices were mentioned. With respect to groundwater shortages, farmers mentioned investments related to improving the capacity of groundwater (groundwater refill), selection of new varieties that are tolerant towards droughts, and improving irrigation efficiency. Among both water stresses, innovations in irrigation are regarded as a main action to be taken to increase resilience and maintain food security.

4. Discussing options for Addressing Water-related Issues

4.1 Reflection on Current Water-related Stress Adaptiveness

When comparing and reflecting on the situation of the farmers in the study region in the VMD in relation to adaptiveness towards climate change and water-related stress, the results of the EU FERTINNOWA (Transfer of INNOvative techniques for sustainable WAter use in FERtigated crops) project can be used (FERTINNOWA, 2018). The main objective of the FERTINNOWA thematic network was to create a meta-knowledge database of innovative technologies and practices for the fertigation of horticultural crops in Europe and to exchange knowledge on existing and novel technologies (innovation potential, synergies, gaps, barriers) for fertigated crops and ensure wide dissemination to all stakeholders involved of the most promising technologies and best practices. In this project, a Benchmark Survey was executed to generate an overview of the current status of technology and knowledge implementation in different European regions, growing systems and crops where fertigation is applied. The survey also gathered information on perceptions and behaviours regarding irrigation and fertigation management in fertigated crops with 371 farms surveyed, covering a total of 531 cropping systems including soilless and soil-grown crops both outdoor and covered. The surveyed farms were located in the main European horticultural production countries, including Spain, Italy, France, Belgium, the Netherlands, Poland, Slovenia, the United Kingdom and South Africa.

The main findings were that also in the EU there are various concerns on the availability and quality of freshwater. Groundwater was identified as the most applied water source for irrigation practices, with 60% of the respondents using this source while shortages were regularly observed. Water storage was considered to be important in overcoming water shortage issues. However, respondents who stored water also faced different bottlenecks: lack of space for rainwater storage, maintenance requirements, leaking, material degradation, and the presence of unwanted material in the water (e.g. algae or microalgae). Stored water was also sensitive to external particles such as sediments, leaves, bird or fish droppings. Similar problems can be expected in the VMD where location for water storage is very limited. Water storage could however provide a solution for livestock farmers who require lower quantities of water compared to crop farmers who rely on large quantities of irrigation water. Another possibility is underground storage although that requires large investment costs which will be difficult for the mostly marginal farmers in the VMD. The FERTINNOWA project (2018) also assessed the usage of high-tech solutions such as water treatment facilities. Although this is also possible in the VMD, the adoption of high-tech solutions will remain limited for marginal farmers, although there is a potential market for farmers within the industrial and consolidated food system which focus on agricultural/livestock/aquaculture production for export and require inputs with good quality.

Concerns on water availability and quality in EU are similar to the region investigated in this study; the main difference, however, is that the EU horticulture sector has more tools and technologies to adapt to this, and measures such as moving or dropping crops because of natural stresses were not seen in FERTINNOWA (2018).

4.2 Water- and Soil-related Transition Pathways

4.2.1 Possible Water and Soil Management Measures The increasing salinity of water resources due to climate change and land subsidence and other anthropogenic influences such as upstream dams is a main issue with respect to agricultural production, particularly in coastal zones of the VMD. The study also revealed that groundwater shortages are a main concern for farmers. As such, since multiple water-related problems are occurring at the same time, the main part of the solution is to improve freshwater storage, field-level irrigation and soil management practices aiming at dealing with saline water and increasing water-use efficiency. Farmers from the household interviewed also indicate that such investments are required. An overview of possible measures includes the following:

(i) Freshwater storage and treatment to serve as a buffer in the dry season. This is especially relevant in the coastal region where currently vast quantities of groundwater are used. Storage could be made in jars and tanks for particular usages for livestock and/or freshwater aquaculture.
(ii) Increasing water productivity of agricultural production systems through irrigation innovations. In this context, continuous flooding, alternate wetting and drying, sprinkler, drip, furrow and surge irrigation can be considered.
(iii) In situ water treatment to make stored freshwater and saline or brackish water more suitable for crop and livestock production. In this context, treatment technologies for partial desalination of water can be considered, like physical–chemical technology or biodesalination technology, and also treatment technologies to remove pathogens and toxic organic compounds from stored surface water and stored rainwater.
(iv) Increasing soil organic content. Besides measures in the agricultural water management field, it is also relevant to improve the soil organic carbon content. Soils with sufficient and sustainable organic carbon content have a large water-holding capacity and a good measure to deal with droughts and water shortage. Furthermore, organic carbon improves the soil structure and stability, which helps in optimising moisture balance for crops. A study by Iizumi and Wagai (2019) found that drought tolerance of crops increased by 16-28% in dry regions. A main advantage of increasing soil organic content is thus that less irrigation water is required for cropping systems. However, salinity intrusion is a risk to maintaining sufficient soil organic content as increased soil salinity leads to changes in microbial activity and, thus, decomposition rates. Thus, effective water management practices as mentioned above are also required to maintain sufficient organic carbon content in soils. Soil organic content can be increased by enhanced incorporation of manure or compost, direct addition of crop residues on top or within soils, planting of cover crops, and agroforestry.

Annex 1 provides a detailed overview of the multiple water storage and retention practices, irrigation practices and water treatment options.

4.2.2 Pre-feasibility of Potential Transition Pathways The pre-feasibility of the water and soil management measures are qualitatively judged by applying multiple criteria ranked from low score (1) to high score (10), based on expert judgement of the authors. Figures 4a–d the synergies and trade-offs of the various measures:

- Storage and retention: Freshwater storage from rainwater and/or surplus surface water collected during the rainy season could be achieved with storing freshwater in jars and tanks, storage basins on ground, and subsurface storage via drainage systems or underground tanks. Subsurface storage does not require space while surface storage (basin) would go on the cost of agricultural land (high score for land requirements). However, subsurface storage is an expensive measure and requires maintenance and knowledge for proper operation. Both surface and subsurface storage allows for potentially large storage capacities suitable for crop irrigation. On the contrary, jars and tanks near buildings require little space, are relatively cheap and do not require much labour and knowledge for operationalisation, but storage volumes are relatively limited, which makes it difficult for usage for crop irrigation.

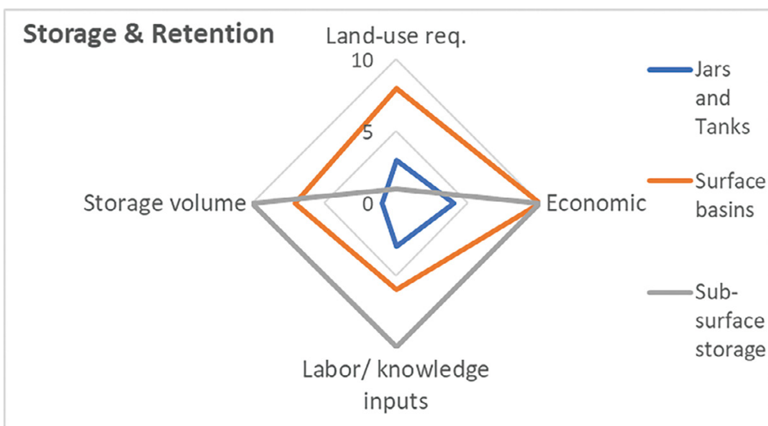

Figure 4a. Synergies and trade-offs of water storage and retention measures

- Irrigation practices: The water-saving potential is largest for drip irrigation, sprinkler and surge/furrow irrigation practices. However, more advanced technologies come with higher price and require labour and expertise. Surge/furrow and drip irrigation would be suitable for brackish/saline conditions; these practices cause different salt concentration zones in soils, and crops can be planted within the lowest concentration zones. Also, continuous flooding and alternate wetting and drying would be sufficient practices under brackish/saline conditions, as it allows for regular drainage to remove excess salt. Land-use requirements are low for all irrigation practices, although surge/furrow would require some space. It should also be noted that flood irrigation and alternate wetting and drying are more suitable for rice cultivation, while the other irrigation methods would be most suited for other crops and orchards.

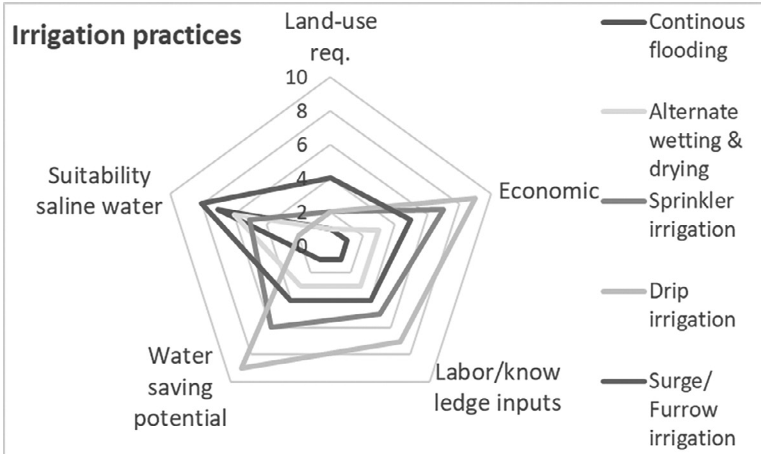

Figure 4b. Synergies and trade-offs of irrigation practices and techniques

- Water treatment technologies: Almost all of the physical–chemical treatment options like evaporation/condensation processes or membrane separation processes are quite expensive for desalting or purifying water for irrigation purposes, especially at a small scale. Biodesalination processes with algae or biopurification processes with wetlands might be a more feasible alternative, but only if the space required can be combined with the production of valuable crops. The labour and knowledge inputs of all technologies are rather high, as these are more advanced technologies which require knowledge on operation and maintenance. Nevertheless, these technologies are able to treat water to good quality, even to drinking-water standards.

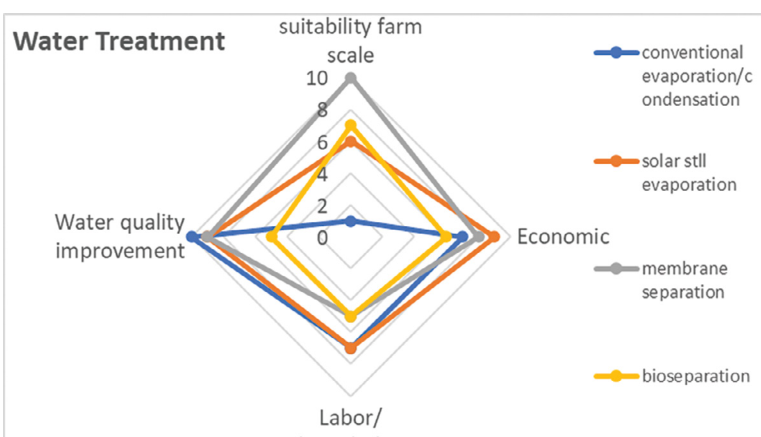

Figure 4c. Synergies and trade-offs of water treatment technologies

- Soil management: Increasing soil organic content is a relatively cheap measure as waste materials (straw) can be used and the method does not require extensive labour and knowledge. Increasing organic content of soils is well known to have a positive effect on the water storage potential of soils. In addition, organic amendments are known to reduce the effects of salinity on soil microorganisms, therefore positively influencing microbial activity and nutrient cycling (Wichern et al., 2020)

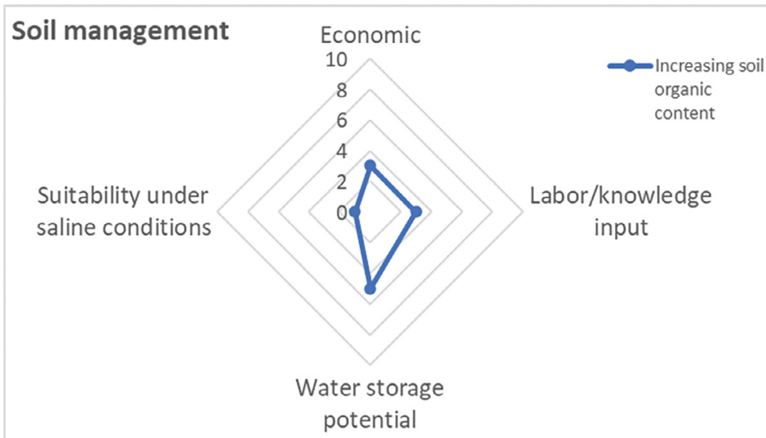

Figure 4d. Synergies and trade-offs of soil management (increasing soil organic content)

4.2.3 Agricultural Water- and Soil-related Transition Pathways Possible transition pathways from an agricultural water and soil management perspective on farm is presented in Figure 5 for various crop production systems, livestock farming and aquaculture based on the pre-feasibility assessment.

Vegetable and fruit trees cultivation mostly takes place in furrows where the didges are filled with surface water and rainwater in rainy seasons and groundwater during dry seasons. Didges are usually filled depending on observed crop water requirement by farmers. Improvements in irrigation management can be achieved by only filling one side of the furrows, which can not only save water but also allow for cultivation when water becomes more brackish. Filling only one side of furrows causes different soil salinity zone in the raised beds, and crops can be cultivated on the lower-soil-salinity zones. Irrigation technologies aiming on reducing water use include sprinkler and drip irrigation, and, when properly operationalised, these can work sufficiently under brackish conditions. However, such technologies need pre-treatment of water to remove solids to prevent clogging of nozzles, which requires additional costs compared to furrow irrigation. Increasing soil organic content is encouraged for both cultivation systems.

Rice is mostly cultivated under continuous flooding with surface water (and rainwater) in rainy seasons, while in dry seasons surface water and even groundwater are applied.

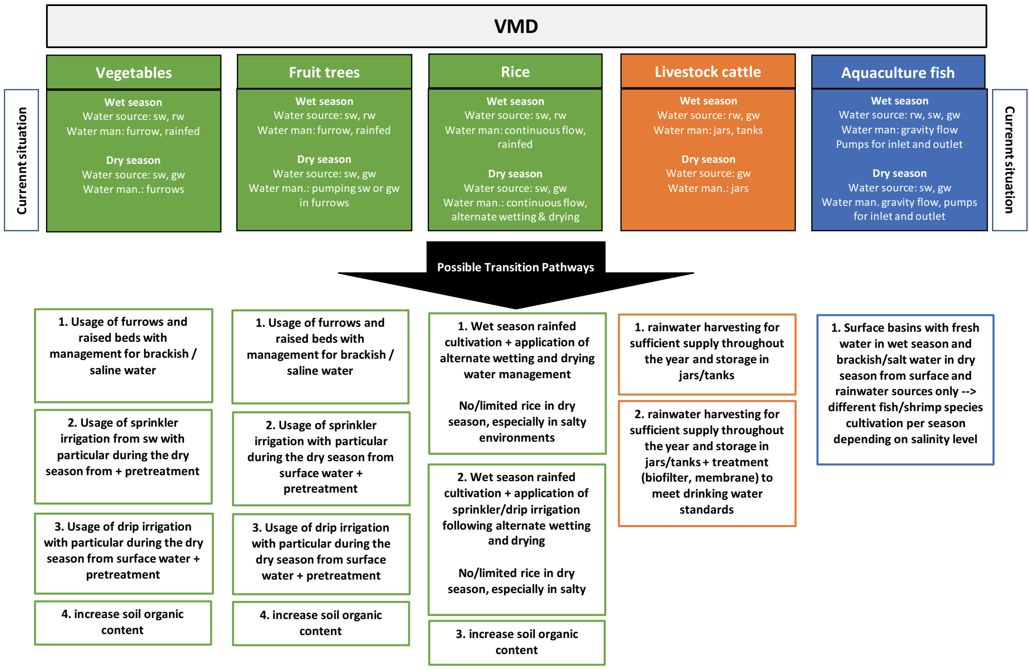

Figure 5. Identification of possible water- and soil-related management transition pathways in the Vietnamese Mekong Delta. Note: sw: surface water; rw: rainwater; gw: rainwater.

Shifting to alternate wetting and drying helps to increase water productivity of rice cultivation and can provide a big gain in water savings as most of the delta is cultivated with rice. Cultivation of rice in regions affected by salinity intrusion should not be carried out in dry seasons, as the current practices of using fresh groundwater resources are not sustainable. Instead, it is advised to apply other crops which require less water and are more salt-tolerant compared to rice in salinity-affected regions.

Rainwater harvesting, such as in jars and tanks near buildings, may provide sufficient freshwater for keeping livestock. The advantage is that storage of rainwater also allows for livestock rearing in areas affected by (severe) salinity intrusion. The usage of water treatment technologies of harvested rainwater would allow for producing water with drinking-water standards, which has additional benefits as it reduces water-related diseases of animals and, thus, results in more production.

Aquaculture takes place in almost all Mekong Delta regions with mostly freshwater fish at the inner delta and brackish/saline aquaculture at coastal zones. Most fishponds are directly connected to canals which with tidal regime allow for refreshment of pond water. However, fully controlled ponds (e.g. shrimp farming near the coast) also use groundwater to keep water quality optimal for cultivated fish/shrimp, which is unsustainable. It is therefore important that selection of fish/shrimp types should be based on the natural water quality of surface water (salinity) to adapt to changes in water salinity during seasons and aggravated by climate change over time.

4.2.4 Water Governance Most of the required investments proposed in this study require involvement of governmental agencies; from a financial perspective, implementation facilitation to advisory services (e.g. through agricultural extension services). Therefore, the proposed interventions need to fit with national and regional policies and action plans. In November 2023, the Vietnamese government enacted the Law on Water Resources (28/2023/QH15). It provides for management, protection, regulation, distribution, restoration, development, extraction and use of water resources (The National Assembly of Vietnam, 2023). The law mentions the need to apply advanced, economical and effective irrigation technologies to address current and future water challenges (climate change, salinity, among others mentioned in the law) in Vietnam. It also states the need for investment in and construction of irrigation dams and reservoirs.

The long-term vision and strategy for the Mekong Delta is presented in the Mekong Delta Plan (Mekong Delta Plan, 2017). It presents a roadmap for sustainably living with water with short- to long-term investments until 2100. This plan also highlights the preservation of water as a priority target and proposes development of freshwater storage facilities to secure freshwater during dry seasons to maintain cultivation within the horticulture and fruit sectors. Also, increasing rainwater harvesting is explicitly mentioned as one of the short- to medium-term investment areas.

This law on Water Resources and the Mekong Delta Plan are only two of the major legal instruments relevant to the investments presented in this study. It shows that there is a strong legal framework on water management and that the proposed transition pathways of this study fit within this framework. It should also be noted that there is a strong network of institutions working in this domain, including various Ministries, various river basin organisations, research and education institutes, and multiple private companies. The main challenge, however, remains proper coordination and implementation of measures as well as sufficient collaboration and sharing of responsibilities between stakeholders (Mekong Delta Plan, 2017).

5 Conclusions and recommendations

In the coastal zones of the MD, crop irrigation is mostly done with canal water and/or rain-fed. These water sources are particularly used during the wet season. A main secondary source is deep well water. Livestock water source is mainly deep well water throughout the year. Overall, main dependence on deep well water for agriculture and livestock purposes is observed, although this is risky as it is a limited freshwater resource.

Rainwater is widely available, particularly during the wet season, and, therefore, widely used for agriculture purposes and drinking. The most limiting factor, however, is the storage capacity. The quality is mostly good when compared to WHO drinking-water guidelines, although contamination with coliforms and metals (lead) and other contaminants are observed. Canal water is sufficiently available throughout the year for crop irrigation and, therefore, often used by farmers. However, there are many quality concerns related to this water source, which include elevated levels of coliforms, pesticides and locally present metals. High salinity concentrations in this water source are an increasing concern due to low-lying lands in combination with sea level rise induced by climate change. Groundwater is available through wells which are used by many farmers in the coastal regions. The quality varies per location with local higher concentrations of iron and other metals and sometimes coliforms. However, the largest quality risk is associated with the increased salinisation of this water source, which is caused by overexploitation and sea level rise, among other reasons. Overall, all water sources have concerns with respect to the presence of microbial and chemical pollution. This is a risk to food safety due to possible accumulation of hazardous substances in edible food products in the production phase, thereby entering the food system. Furthermore, the current pollution status is a threat for supplying safe drinking water. In addition, surface water and groundwater also have salt-related risks, which is a direct threat to crop and livestock production.

Currently, farmers in coastal regions observe water-related problems with respect to (increasing) salinisation of water sources and shortage of groundwater. Current adoption measures applied include development of mixed freshwater/saltwater agricultural production systems, planting alternative crops and using alternative water sources. Farmers would like to see more investment related to more salt-tolerant varieties, groundwater-refilling activities and innovations in irrigation management to help them address freshwater shortage problems. Overall, the adoption of advanced irrigation technologies and measures such as sprinkler and furrow irrigation and other practices to increase soil organic carbon are recommended in the agriculture activities in coastal zones of the MD. For livestock rearing and aquaculture, investments should be made in rainwater harvesting and treatment to provide sufficient water with good quality throughout the year. Aquaculture activities could also make use of rainwater harvesting practices to provide as a buffer when canal water becomes too saline for certain fish species.

Supplementary Data

Annex 1: Water storage, irrigation practices and water treatment solutions

A1.1 Water storage and retention

Freshwater storage is particularly interesting in regions where natural freshwater sources are lacking in the dry season. This is particularly the case during the dry season in the coastal Mekong Delta when surface water is fully salinised and fresh groundwater sources get depleted. The following overview presents various water retention and storage measures which could be applied on the farm level.

- Jars and tanks
  Within particular coastal regions where fresh supplies are lacking during the dry season, farmers install water storage tanks (e.g. cement or plastic). These tanks are filled with rainwater which is harvested from rooftops. These storage tanks are installed by either farmers themselves or via community initiatives of public buildings such as schools which have generally larger roofs. The stored water is used as freshwater source for human consumption as well as for livestock.
- Surface basins
  Besides storage in tanks, the coastal regions also invest into the development of surface basins such as artificial lakes and canals to store fresh rainwater and surface water. Within the province of Ben Tre, for example, the government has constructed artificial lakes for freshwater supply to communities and livestock. Moreover, new lakes are in the planning for the upcoming years (Vietnam Express, 2020). Nevertheless, such lakes require valuable space (e.g. Lac Dia Lake is 57 ha), and in the dry season there may be a risk of water salinisation. Also, farmers could dig their own pond for water storage. However, sufficient dredging and drainage in the rainy season are required to maintain low salinity levels during the dry season.
- Subsurface storage
  A system which can be applied on the farm level is installing underground tanks. Such tanks can be installed directly under the root zones of crops or trees. Due to capillary rise, the water from tanks rises to surface level where it is available for plants. The main advantage of such a system is that it does not require space, although investment costs are rather high.

A1.2 Advanced irrigation techniques and practices

In order to maintain agricultural and livestock production systems under increasing saline conditions in the Mekong Delta, improved irrigation practices are required both in the floodplains (upstream) and in the coastal (downstream) regions. When applied effectively to the upstream flood plains, this results in higher quantities of water available for downstream (coastal) regions to halt or reduce inland sea water intrusion and provides increased possibilities to drain and flush salinised soils. Effective irrigation in downstream regions affected by salinity (intrusion) allows for more agriculture production. The following overview presents multiple irrigation techniques and measures which make more effective use of freshwater:

- Continuous flooding (CF)
  CF of water on fields is generally applied in rice cultivation in the Mekong Delta and provides a good growing environment for rice. After rice is planted in the fields, water levels are around 3 cm initially and gradually increase to 5 to 10 cm (with increasing plant height) and remain until the field is drained to secondary canals 7 to 10 days before harvesting. For direct wet seeded rice, field should be flooded only once the plants are large enough to withstand shallow flooding (IRRI, 2021). Irrigation is done via pumping water in and out of the fields from canals in addition to rain (or sometimes from the groundwater, because surface water and rainwater may not be available in the dry season). This type of irrigation consumes large quantities of water, although improved measures can be taken to reduce water loss: (i) through developing (concrete) irrigation and drainage canals per field; (ii) carry out tillage prior to planting and irrigation to remove cracks as these cause water losses from the fields; (iii) develop solid bunds and prevent cracks and holes. Nevertheless, water productivity is rather low with this type of irrigation.
- Alternate wetting and drying (AWD)
  An alternative to CF of rice fields is AWD, which is based on maintaining water levels below the surface area (approximately 5–15 cm below surface area). Another variant is to provide water to fields to keep the soils fully saturated only (SS). This irrigation practice requires monitoring of soil's moisture and groundwater levels via shallow tube wells. Water may still be irrigated via pumps from canals, although more advanced technologies such as drip irrigation (see more information later) may be applied to maintain sufficient soil moisture content. The advantages of crop water productivity compared to CF in the Mekong Delta are between 6% to 14% and 10% to 17% for AWD and SS, respectively (Thanh et al., 2008). Further advantages are energy-savings due to reduced pumping requirements and reduction of methane emissions due to more aerobic soil conditions. However, it would require training farmers to learn how to operate, maintain and monitor such a system. In addition, investments related to monitoring soil moisture and groundwater levels are necessary. Rainwater during the wet season is however required to drain soils to remove accumulated salts from such irrigated systems.
- Sprinkler irrigation (SpI)
  Irrigation by sprinkler allows for more efficient use of water compared to the flood irrigation method. Most effective use is achieved when watering quantities and patterns over time (day and season) are in line with crop needs (Zaman et al., 2018). This

would require knowledge on crop growth and water demand of specific crops in the Mekong Delta. Various types of sprinklers are available, including fixed sprinklers and moving systems. Sprinkler systems also allow for effectively leaching salts from the surface as under this irrigation system salinity build-up occurs in the subsurface soil. A disadvantage of the system is the need for pumps and electricity, as it is a pressurised irrigation system.

- Drip irrigation (DI)
  DI system supplies required quantity of water to the crop on a daily or periodic basis and delivers water very close near the plants through pipes (Zaman et al., 2018). The pipes contain a series of spaced emitters, and the system leads to higher water-use efficiency. A dripping irrigation system can also be installed under the surface (subsurface DI), which releases water near the root zones of crops to further reduce water transpiration from soils. A disadvantage of the system is that salts may accumulate in the surface, although highest concentrations are observed in the middle of two dripping pipes. Thus, various saline zones in the surface layer (varying from high to low salinity) will occur. Moreover, higher salinity concentrations in the top surface layer can be expected under subsurface DI compared to surface DI. Overall, the positioning of drip pipes is crucial to prevent crop damage due to soil salinisation. Regular drainage of soils, particularly in the wet season, is in any case required to leach salts out of the agricultural system. Another point of attention is the clogging of emitters, which should be controlled periodically.
- Furrow irrigation (FI)
  FI is based on growing crops or fruit trees on raised beds surrounded by small ditches or furrows. The furrows can be filled with freshwater during the wet season, which becomes a buffer or storage during the dry season. This practice is often executed in orchard fields, but it can also be applied for vegetable crops. However, when furrows have to be refilled with brackish or saline water during the dry season, the salts quickly accumulate into the root zones when crops or trees are installed in the middle of the beds. Therefore, regions under salinity pressure (e.g. coastal zone) should manage the furrows on alternative ways through (i) keeping one half of the furrow empty during dry periods and completely filling another furrow with brackish or saline water or (ii) developing beds on slopes (instead of flatbeds). This adjustment will assure salt accumulation on the edges of the beds instead of the plant/tree root zones (Zaman et al., 2018).
- Surge irrigation (SuI)
  Surge irrigation uses a surge controller butterfly valve placed in the centre of the field with gated pipe leading out of the valve going both directions along the top of the field. The water will be pumped on the field within certain interval (and not continuously) at different sites of the agricultural field. The alternating flow of water on each side of the valve causes an intermittent wetting and soaking cycle in the irrigated furrow. This causes soil particles to settle to the bottom of the furrow and can reduce the water intake rate of the soil. Therefore, less water will be lost through soil infiltration, and, as a result, crop water-use efficiency increases.

This irrigation type is specifically interesting when water savings have to be achieved for crops with shallow root systems, such as sugarcane and corn. Nevertheless, SuI requires constant availability of freshwater resources and comes with additional material and pumping costs compared to CF. Furthermore, it requires sufficient knowledge of the environmental system to adequately define and implement watering intervals.

A1.3 Water quality improvement options

The salt content of the water needed for irrigation can be reduced by desalination technologies. The majority of desalination technologies are based on physical–chemical separation principles. An overview of technologies and the principle behind the technology is shown in Figure A1 (Curto et al., 2021).

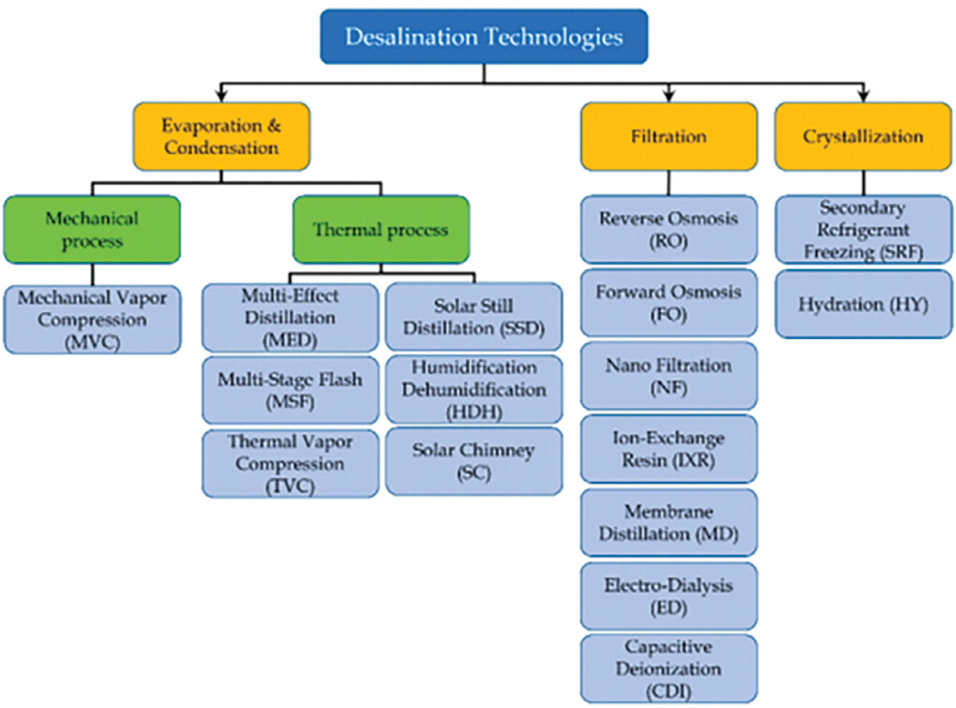

Figure A1. The classification of desalination technologies by working principle.

Desalination technologies applied on a large scale are MED, MSF (thermally driven) and RO (electrically driven). MED and MSF are conventional evaporation/condensation technologies that cannot be downsized to a very small scale. Reverse Osmosis (RO) is a modular membrane process that can be downsized to a small scale quite easily.

Besides applying physical–chemical separation processes, there is tendency to investigate the potential of nature-based solutions for separation. One of these solutions is the use of algae for desalination (Sahle-Demessie et al., 2019). Specific types of algae reduce the salt content of the water. The principle of the salt uptake is still unclear, and the technology is in the development stage. Besides its use for reduction of salt in water, the algae can be harvested and used for biofuel or as protein source.

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