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A computational modelling approach based on the 'Energy - Water - Food nexus node' to support decision-making for sustainable and resilient food security

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ABSTRACT

This study introduces a computational decision framework to achieve sustainable and resilient decentralised energy, water, and food (EWF) systems at the national level using the 'EWF nexus node' approach. The methodological framework was systematically developed based on a hybrid approach using GIS modelling, Analytic Hierarchy Process (AHP), and an optimisation functionality to enable efficient management of spatially distributed EWF resources for resilient food security. It was then applied to dairy and fodder farm case studies in Qatar considering the impact of weather, soil and water factors on these systems. Risk identification and analysis concluded that the weather and groundwater factors are critical for dairy farms, and if they exceed the acceptable limits, it is likely to affect dairy cattle's health and milk production. On the other hand, the groundwater and soil factors have the highest impact on the fodder farms. A new EWF nexus node was then introduced at an optimal location, which would operate at a minimum cost, including the cost of groundwater pumping, desalination and transportation, whilst reducing the risk levels of existing EWF nodes tremendously.

1. Introduction

Many countries worldwide are intensifying their local food production as a means to enhance food security. Dairy farming, a critical industry within the food sector, is a significant contributor to the global economy and the livelihood of households in many countries. Recently, the demand for milk and milk products has increased gradually, which is mainly due to population growth, changes within consumption patterns, continued food value chain modernisation and the booming tourism sector. The management of energy and water in dairy farming is essential to maintaining healthy animals and sufficient milk production. Currently, water requirements for many dairy farms are supplied through groundwater to ensure stable and reliable pressure supply (O'Connor & Kean, 2014), noting that it is expected water requirements will increase as milk production increases (Agrismart, 2016), which on average amounts to 7.42 L of water consumed to produce 1 L of milk (Shine et al., 2018). This may eventually lead to pressures on local water supplies, especially during summer season and periods with minimal rainfall. Similarly, energy is needed in dairy farming for milking, cooling, storing, ventilation and lighting process, where on an average 38.84Wh are consumed to produce 1 L of milk (Shine et al., 2018). The largest of the energy consuming processes are milk harvesting and milk cooling (Rajaniemi et al., 2017). Thus, the energy cost per litre of milk for dairy farms could increase without an effective mitigation approach, this is due to having an infrastructure for milk farm that is not optimally designed for rising milk production levels. Moreover, high energy consumption during the day or peak hours will negatively impact competitive market setting, national grid loads and electricity costs of dairy farms (Upton et al., 2013).

Due to increased resource uncertainties across energy, water and food sectors, a nexus approach to resource management was first introduced in the 1980s, notably in a project by the UN University entitled: Food-Energy Nexus program (Sachs & Silk, 1990) as part of efforts to improve security across the three resources, through the integrated management and governance across various scales and sectors. Incidentally, there are inherent interdependencies and trade-offs that exist across Energy-Water-Food (EWF) sectors in what is known as the 'nexus' of the three resources, which was first introduced at the Bonn Nexus Conference in 2011 (Dombrowsk,y 2011). From this perspective, the energy, water and food (EWF) nexus is theoretically an effective approach to identify the synergies and trade-offs that may exist in the design and operation of EWF resource systems, and measure the environmental

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burdens whilst delivering products and services (Al-Ansari et al., 2015; 2017). Consequently, introducing a modelling framework for the design and operational decisions in conventional EWF nexus systems is expected to enhance their environmental, economic and social dimensions of sustainable development, whilst achieving the security of EWF resources. In this regard, the integration of EWF Nexus with decision making methods, such as optimisation, agent-based modelling and game theory are crucial for successful resource management integration (Namany et al., 2019). Recently, a study conducted by the current authors demonstrated that the EWF Nexus "node" approach is an effective model for geospatial risk assessment of various food systems and agricultural sectors (Haji et al., 2020). This paves the way for further optimisation and decision-making, such that the impact of different types of risk factors can be minimised, thus improving the resilience of EWF systems on a national level. Accordingly, this study proposes an optimisation framework which integrates the EWF nexus node model to deduce solutions for risk management. The framework is applied to a case study that considers dairy and fodder farms in Qatar, outcomes of which will support in the effective management of integrated EWF resources and hence achieving sustainable and resilient food security.

1.1. Food security and the energy water and food nexus

Every country desires a sustainable food system to ensure food security, the unpredictability of which on a global scale is due to the complex and dynamic relationship between social, economic, and ecological factors that facilitate food security outcomes at different human and institutional levels. For instance, ongoing food security issues in various areas around Asia and Africa countries remains one of the challenges that needs to be addressed. Issues pertaining to food insecurity are expected to worsen as a result of rapid population growth, overexploitation and scarcity of natural resources and other unprecedented challenges such as climate change and the growing demand for biofuels. Climate change creates dynamic challenges for many energy and water sectors in addition to food producers (Hanjra et al., 2013). Future predictions indicate that by 2030, the needs for EWF resources are expected to grow by 40%, 25% and 50%, respectively, thus posing many challenges (Madani et al., 2015). Moreover, the food industry is constantly under stress due to shear complexity of the system which is dependent on water and energy. If these stresses are not addressed, extreme social and economic problems may occur, and result in poor food security outcomes in the form of food utilisation, availability, accessibility and stability. Therefore, many food sectors are essentially seeking to guarantee continuous food production in order to achieve food security (Vieira et al., 2018). Today, farming systems are threatened by a large number of environmental, social, economic and institutional difficulties (Daugbjerg & Feindt 2017; Maye et al., 2018; Purnhagen et al., 2018; Burton & Fischer, 2015; McGuinness & Grimwood, 2017; Saifi & Drake, 2008; Diogo et al., 2017).

Considering the complexity of EWF nexus systems, it is necessary to develop tools and indicators that can accurately evaluate their performance in order to inform and improve decision making within food security scenarios (Namany et al., 2019). The fact that environmental problems are complex rendering measurement difficult, indicators can provide a simplified representation of the environmental state which can be easily communicated to policymakers. Govindan & Al-Ansari, (2019) introduced a computational framework to expose EWF systems to the complex nature and associated risks of external uncertainties in the nexus. The authors demonstrated that using the developed frameworks will provide the capabilities to track and mitigate emerging risks that can create enormous disturbances in the operations of integrated natural resources systems. Furthermore, indicators can be used to determine and assess the geographical distribution of areas, and to link anthropogenic behaviour to environmental impacts as synthetic knowledge in Geographic Information System (GIS) representations (Rubio & Bochet, 1998). From this perspective, visualisation techniques, such as GIS are becoming increasingly popular as they are able to translate rich and complex information into spatially driven visual representations (Monika et al., 2015). Such applications, is important for resource management, as with the case of EWF nexus. In dairy industry, the conceptualisation and implementation of GIS is a very challenging task, especially if the data are distributed on various stages of the supply chain and tool needs to be implemented in an effective manner for decision making. A study by Kumar et al. (2012) proved that GIS is a beneficial tool for practical and effective decision making. The authors utilised analytical tools within GIS, such as: proximity analysis and buffering tool in order to optimise and make a quick business decision on the potential and expenditure of milk procurement for various villages. Moreover, models for simulation provides additional methods for system investigation and analysis, in addition to problem detection and solution identification (Stamou & Rutschmann, 2018). However, since GIS is powerful in evaluating and locating business opportunities (Gardner & Cooper, 2003), it can be utilised to optimise decision making in terms of procurement expenditure, recognition of new procurement areas or even segregating businesses into input services, rural milk marketing and milk products. Thus, GIS is valuable for realistic, efficient and rapid visual based decision making.

In the case where the indicators for the desired problem at the required level or scale are not available, then new and specific indicators can be developed (Flammini et al., 2013). This is important in the EWF nexus studies, as problems and questions within the discipline can focus on different parts of the nexus and seek to address various challenges that may or may not have been considered previously. Fundamentally, it is important to understand some of the resource sub-systems that can be represented within the EWF nexus and are relevant to the case study. Despite the difficulties involved in conceptualising and implementing GIS for many food systems. Kumar et al., (2012) utilised proximity analysis within GIS as an analytical tool to encourage buffering in decision making, such as brining new villages as procurement centres. Moreover, integrated models such as combining mathematical programming and analytic hierarchy process (AHP) techniques were proved to be an efficient tool for optimal criteria selection in different industries (Verma & Mehlawat, 2017). As such, Sharma & Pratap (2013) utilised AHP method to identify and create a hierarchical risk factors for supply chains and perform risk optimization for the most critical factors affecting the supplier and supply chain companies. Recently, Haji et al. (2020) introduced the EWF Node to represent the decentralisation perspective of integrated EWF Nexus systems, and to introduce elements of risk analysis and resilience. The study utilised the EWF nexus node, where each node represented a food sector sub-system, including open field farms, conventional and hydroponic greenhouses, where they considered as a function of energy, water and food, and can be affected by exogenous risks, such as climatic, water and soil factors. Then, spatial risk factors were gathered, digitalised, and incorporated into a single geo-processing framework from various data sources focused on the food industry, allowing the visualisation as well as the further processing of risks. Thus, a composite geospatial risk maps for the different food production scenarios were then generated using AHP. In this study, the main focus was on open field farms, conventional and hydroponic greenhouses, where they are a function of energy, water and food. The analysis proved that the weather factors such as temperature, solar radiation and humidity has highest impact on open field farms with AHP relative weights of 0.18527, 0.16860 and 0.15785, respectively. However, groundwater factors increase the risk level in conventional and hydroponic greenhouses.

The resilience of a system operating in risky conditions can be described as its ability to adapt and/or recover from unpredictable disruptions and consequently minimise potential damages, thereby sustaining its ability to function continuously and meet its necessary economic and societal objectives. Importantly, resilience can support system stability while aspiring to achieve the sustainable development objectives and security through availability and access (Louisot, 2015). Furthermore, the concepts of security, sustainability and resilience are often used interchangeably as they have several correlations and interrelationships. In order to efficiently develop resource systems and monitor their performance, the principles based on sustainability, security and resilience should be incorporated with the EWF nexus approach to guarantee a reliable assessment of the three sectors. In view of this, several studies have demonstrated the nexus framework as an area for integrated resource modelling that demonstrates useful results in a multi-objective and stochastic optimisation as they can cope with the complexities (Garcia & You, 2016). Namany et al., (2021) proposed a holistic assessment method using the AHP modelling technique based on the EWF nexus to develop a decision-making system that considers critical economic systems, which require urgent management through assessing their sustainability, security, and resilience levels, in order to support policymakers in establishing national priorities and sectorial strategies. Another study by Shu et al., (2021) developed a composite EWF resilience index comprises of two sets of indicators: one indicating the availability level of EWF resources with respect to the three energy, water and food sectors, and the other indicating accessibility of population to resources at the household level. The two sub-indicators were computed individually within the EWF and household sectors. This proposed composite index could be used to evaluate the resilience of EWF systems against disturbances in the context of high energy, water and food accessibility and availability.

1.2. Food sector - dairy farms

Globally, dairy farming considered as one of the critical leading industries within food sectors. However, they are responsible for a significant proportion of land use, water consumption and environmental burdens including nutrient losses and pollution emissions to the air and water. Due to the growing demands for dairy products, the energy consumption in dairy farming has increased significantly over the past 20 years (World Livestock 2011, 2011). Furthermore, roughly 2,128 Mt CO_2 per year are emitted by dairy production, which is approximately 5% of global anthropogenic emissions (Burke et al., 2009). The environmental burdens will continue to increase due to the continuous demand for dairy products, unless the efficiency of dairy production are to be improved (Steinfeld & Gerber, 2010). Frorip et al., (2012) proved that energy conversion is poor in livestock production, due to the fact that when crops are fed to livestock, a huge amount of energy is consumed on maintaining body metabolism and only a small energy share is utilised for meat and milk production. Accordingly, Hosseinzadeh-Bandbafha et al., (2018) utilised the data envelopment analysis (DEA) technique to assess energy flow and analyse wasted energy in order to achieve higher energy efficiency and less GHG emission in a dairy farm.

Besides the effect of volatility in milk prices, the environmental issues associated with livestock and dairy activities, the processing of milk and the management of agricultural waste and manure cannot be ignored or overlooked. The challenges range from energy usage and consumption, water and land footprints, emissions of greenhouse gases (GHGs), runoff of nutrients and lost opportunities to recover resources. Recently, (Luqman and Al-Ansari, 2021) proposed a novel polygeneration system that functioned using the various types of dairy farm wastes in an integrated manner such as, manure, wastewater and the very low concentration of produced methane from the barns. The proposed system is also equipped with a hydrogen cycle that tackles the societal issues related to reusing the wastewater. with an overall energy efficiency computed to be 35.2%

In terms of assessment, Mann & Gazzarin (2004) indicated that life cycle assessment along with economic business indicators can be combined in a single assessment and used to assess the sustainability of dairy farms. Similarly, Gonzalez-Mejia et al., (2018) illustrated a comprehensive trends analysis to evaluate the sustainability of agricultural intensification and sufficiently capture heterogeneity within farm operations. The method considered 16 indicators related to farm structure, environmental and socio-economic aspects of sustainability, which was integrated with the comprehensive clustering-based method. Two main clusters were defined: extensive and intensive clusters. Extensive farms cluster depends on expansion of grass-based milk production, with lower milk yields and labour intensity. However, intensive farms cluster focus on higher milk production per cow and less labour per hectare. Thus, this indicated that the extensive cluster intensifies slightly faster than the intensive cluster, in terms of milk yield per cow and concentrate feed usage.

Many studies proved that the dairy production system is designed to improve the management systems across various components, in order to support the future dairying in line with ecological and evolving socio-economic dimensions. Recently, Patel et al., (2019) categorised the dairy production system in India based on its functional dynamism using a composite index of dairy production system. The composite index was established by means of the principal component analysis and based on the optimal combination of 26 indicators. Twenty states in India with high contribution to the overall milk production were selected and divided into three groups, namely, dynamic, transient and subsistence dairy production systems. From a water resource perspective, the consumption of freshwater within livestock sectors and animal agriculture in many countries is considered an important factor when assessing water environmental sustainability (Ridoutt et al., 2012). Hence,A Kumar et al., (2013) addressed the importance of resolving inter-state disparity with an adequate planning and strategies to meet growing demand of milk. Thus, minimising the resolving inter-state disparity in milk production can be achieved by considering all components within dairy sector as a system. Utilising the system approach will provide a cohesive vision and direction for the dairy sector. As such, Upton et al., (2014) proposed a comprehensive and efficient model of calculating overall energy and water consumption in a dairy farm, through replacing large mathematical models with a much small numbers representing predicted yields, which is empirically derived coefficients, thus allowing energy and water consumption values to be easily estimated. In order to improve the performance of food systems with regard to production, operations or supply chains, mathematical modelling and optimisation have been mostly used. This approach is especially essential in complex dairy systems, which involves human, livestock and cattle, housing, food and feed, climate, water and other components. Although all of these components must be understood and analysed individually, it's equally important to understand their interaction on a system level (Patel et al., 2019).

1.3. Study objectives

Studies on the EWF nexus thus far have focused on the EWF nexus system to study issues related to food security, through applying indicator-based assessments, or mathematical approaches to enhance EWF system without an integrated approach that considers the geospatial component. Going forward, it is important to develop food security strategies that are resilient and sustainable across all dimensions in terms of the management of interdependent EWF resources. Despite multiple use of optimisation methods in dairy farm management and production systems considering the interlinkages between EWF resources, there is no EWF analyses of dairy production using geospatial optimisation with an energy and water risk factors components that has an impact diary production are available in the literature. As such, this study addresses these gaps by expanding on recent work reported by Haji et al. (2020), by integrating a geospatial computational modelling and optimisation approach along with the nexus node for a Qatar study. The benefit behind expanding the geospatial nexus approach developed by the authors, will aid in supporting the decision-making for resource management in risky environments, optimally allocate various resources and reduce the impact of endogenous and exogenous risk factors, thereby enhancing the resilience of EWF systems on a national level as demonstrated for the Qatar case study.

1.4. Qatar case study

Food security will remain a challenge, especially for Middle Eastern countries and those in the Gulf Cooperation Council (GCC) for which the State of Qatar is a part of, since the annual GDP growth rate and per capita income is expected to increase from 1.5% up to 3.6% during 2018-2021 (The World Bank, 2020). In this regard, Latif & Kodzhakova (1970) discussed that while Gulf countries have a steady growth within the economic indicators with a higher GDP growth rate than world average, and significant improvement in the world economic positions, the question of food security remains critical and very severe in these regions. Pirani & Arafat (2016) stipulated that GCC countries will continue importing the majority of food due to the fact that local production is not feasible and cannot be produced locally.

The State of Qatar is one of the richest countries in the GCC and in the world with a high GDP per capita at 183,466 Billion USD in 2019 (The World Bank, 2020). Although it's one of the poorest countries with respect to natural water resources (FAO, 2019). Furthermore, Qatar has historically relied heavily on food imports to meet local demand. As such it is vulnerable to supply shocks and disruptions in imports. In 2010, the production of milk and dairy product in Qatar was approximately 35,300 tons. However, the production volume increasing to 58,500 tons in 2013. Since 2017, Qatar has taken numerous measures to promote and encourage higher domestic production with the aim of reducing reliance on dairy imports, creating a 100 % self-sufficient milk sector (Online Qatar, 2019), by allocating 62,000 square metres for a major dairy project and 500 hectares of land to sustain livestock welfare for the development of fodder (Mordor Intelligence, 2020). Managing food security in Qatar across various groups requires effective decision making to address environmental challenges (e.g. environmental footprints and resource scarcity), trade disruptions, and health challenges (e.g. overweight and untransmissible diseases). Moreover, population growth, improvement in the living standards, rapid urbanisation and economic development have increased pressures on Qatar's scarce natural resources (Grichting, 2017), which need to be accounted for in risk assessment and food security planning. Hence, by operating geospatial information related to the dairy farms or any other EWF systems for the State of Qatar, while integrating this information with a unique composite indicator to reflect overall system performance, which will allow decision makers to: identify specified areas that perform better than others from a risk perspective; perform further optimization and enhance the overall EWF system

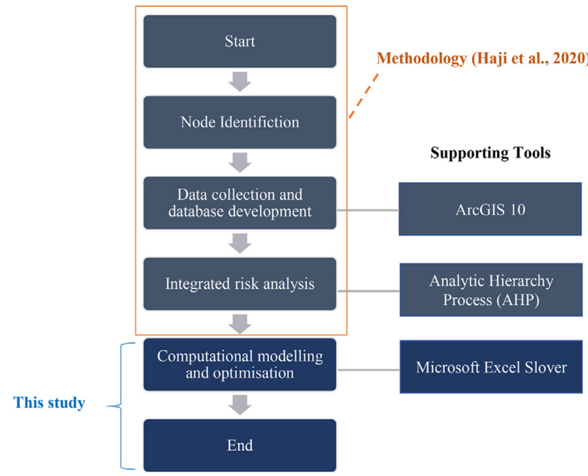


Fig. 1. Nexus Node Identification and Assessment Methodology.

Table 1
The classification of dairy and agricultural industries.

Dairy Node	Fodder Node	Combined/Mixed Node (Dairy and Fodder)
Ghadeer	Irkhaya Farm Mazzraty Farm Hassad Qatar Al Dawoudiya Farm	Al Rawdah Baladna

resilience; and eventually enhance food security whilst limiting environmental impact in challenging environments.

2. Methodology

This study will follow an enhanced version of the methodology reported by Haji et al. (2020) as illustrated in Fig. 1, in which a geospatial optimisation will be performed to identify and propose optimal locations to enhance the overall resilience of EWF system. It focuses on the local and most known Qatari dairies businesses that support the Qatar vision, which includes Baladna, Al Rawdah and Ghadeer dairy farms. Moreover, Hassad Qatar, Al-Dawoudiya and Mazzraty farms are considered in this study as a fodder farms that can potentially supply Rhodes to the dairy farms. Two scenarios will be run using the nodal approach to explore the change within risk factor for the dairy and fodder industries. The classification of industries/farms are illustrated in Table 1.

2.1. The implementation composite risk indicators using AHP method

The analysis is initiated by conducting an Analytical Hierarchy Process (AHP) to assign weights that denote the significancy of various risk factors and hence create the composite geospatial risk indicators. The evaluation process begins by listing all the individual indicators and then to perform a pairs comparison of each single indicators for the specified target. The comparison is made by categorising which of the paired indicators is favourably critical and by how much, which is expressed on a semantic scale from 1 to 9. The AHP is applied on three different nodes; dairy, fodder and combined/mixed (combination between dairy and fodder). For dairy farms, there is 15 pairwise comparisons for the six risk factors. The risk factors are: temperature, humidity, solar radiation, groundwater depth, groundwater salinity and groundwater pH. In Table 2 the factors that are listed on the left are compared one by one with each factor listed on the top so in order to compute the importance of each factor with respect to the goal of selecting

Table 2
Pairwise comparison matrix for Dairy Farm of the six risk factors.

C_jC_i	*Temperature*	*Humidity*	*Solar Radiation*	*Groundwater Depth*	*Groundwater Salinity*	*Groundwater pH*
Temperature	1.00	2.00	1.50	0.67	1.75	1.75
Humidity	0.50	1.00	0.56	0.33	0.33	0.33
Solar Radiation	0.67	1.80	1.00	0.50	0.33	0.33
Groundwater Depth	1.50	3.00	2.00	1.00	0.67	0.67
Groundwater Salinity	0.57	3.00	3.00	1.50	1.00	1.00
Groundwater pH	0.57	3.00	3.00	1.50	1.00	1.00
Sum	4.81	13.80	11.06	5.50	5.08	5.08

Table 3
Risk level of existing nodes.

Farm Name	Node Type	X Coordinates	Y Coordinates	Risk in Summer	Risk Level
Ghadeer	Dairy	51.181986	25.355111	33	Very High
Al Rawdah	Mix	51.181986	25.272749	35	Very High
Baladna	Mix	51.406609	25.699533	22	Low
Irkhaya	Fodder	51.140805	25.003202	205	Medium
Hassad Qatar	Fodder	51.159524	25.040639	230	Medium
Al Dawoudiya	Fodder	51.047212	25.040639	239	Medium
Mazzraty	Fodder	51.2433264	25.6541399	137	Very Low

highly risk farm. Thus, the prioritisation of each individual risk factor or indicator are obtained from analysis.

The same procedures are applied to the fodder and combined farms cases. However, there are other risk factors related to the amount of mineral concentration within the soil are studied. Thus, 36 pairwise comparisons are performed for the nine risk factors for fodder and combined farms, as illustrated in Table A1 and Table A2 (Appendix A) respectively.

Using the Consistency Index (CI) and Consistency Rate equations (CR) with a Random Consistency Index (RI) originated from Saaty (1980), it was then possible to evaluate matrix consistency and verify all assumptions made during analysis. For the dairy farm, the pairwise comparison is applied on six factors, thus the RI=1.24. However, nine factors are used to represent the risk in fodder and mix farm, hence RI=1.45

2.2. Linear programming optimisation framework for EWF Nexus

The final step in this study is to perform a simple linear programming optimisation on the composite geospatial risk map for the both dairy and fodder farms. This technique simply consists of a linear objective function consisting of a certain number of variables, which is to be maximised or minimised to determine optimal solutions by adjusting decision variables depending on the specific number of constraints, where the constraints are linear equalities or inequalities of the variables used in the objective function.

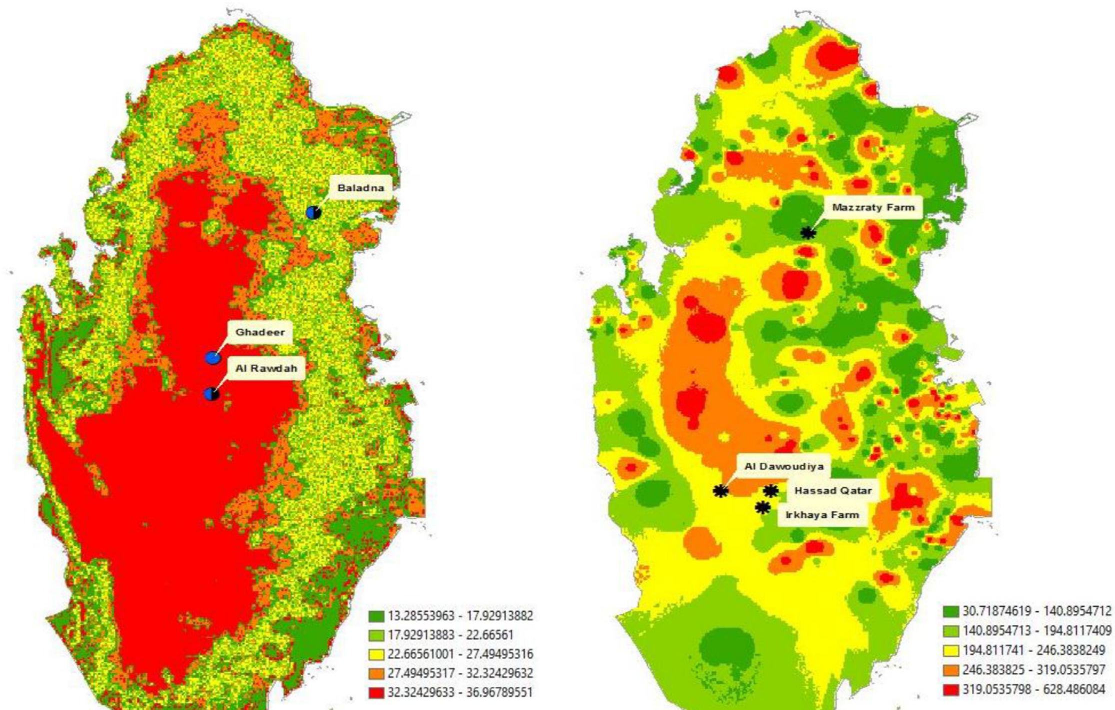
To this point, the current state of existing nodes (three dairy farms and four fodder farms) has been detailed and analysed. Thus, the primary purpose of the optimisation is to minimise the risk of existing nodes located in high-risk areas. Table 3 illustrates that 5 out of 7 existing nodes are located in a high-risk area, this includes, Ghadeer and Al Rawdah as a dairy farm, Irkhaya, Hassad and Al Dawoudiya as a fodder farm. The location of dairy and fodder nodes is demonstrated in Fig. 2(a) and Fig. 2(b) respectively.

The geospatial optimisation can be achieved from two perspectives; either to perform optimisation for existing nodes without introducing a new EWF node, or by introducing a new EWF node to reduce the risk of an existing node. The first option is not an efficient approach, as it is redundant to introduce and invest in new technology without considering the EWF nexus perspective and benefiting from the enhanced food production. Hence, the only option is to invest in a new mix farm (dairy and fodder), where a desalination plant can be installed within a farm; for the purpose of reducing the salinity of pumped groundwater at a new location. In the dairy and fodder farms, water and soil factors are the key triggers for risk level variation. However, weather factors such as temperature, humidity and solar radiation have very minimum impacts on the dairy farm.

The first step in the optimisation is to identify candidate locations that will minimise the overall risk of five existing nodes with minimum operating costs. To do so, a process consisting of three main steps is applied. First, a Sample tool from the Extraction toolset under Spatial Analyst Toolbox in ArcGIS is used to create a single raster map with data from multiple rasters, this includes all rasters. The output map is demonstrated in Appendix C (a) and (d) for dairy and fodder farms respectively, where multiple rasters are converted into 72812 small cells. Thus, the value of each risk factor at each cell (location) can be extracted in a table format easily. The second step is to allocate random nodes on Qatar Map using ArcGIS as illustrated in Appendix C (b) and (e) for dairy and fodder farms respectively. The purpose of this step is to generate limited sample points that can be used for a further process within optimisation. The 72,812 points generated in the previous step are extremely large and cannot be used to run the optimisation problem within an Excel-based Binary Linear Programming Solver. Since the previous sample points have 'no data', then finding the intersection between two maps (raster and sample) is essential. Hence, the last tool which is the Intersect tool from Overlay toolset under Analysis Toolbox is used. The Intersect tool computes a geometric intersection within input features (layers or maps), in which all overlapped layers will be written to the output map as illustrated Appendix C (c) and (f). Thus, 100 random nodes are generated from the Intersect tool having values for each risk factor, which will be used to define objective function and constraints in optimisation problem.

2.2.1. Objective function and decision variables

The objective of this optimisation is to allocate a new EWF node at an optimal location, which will operate at minimum cost, whilst minimising the risk of existing nodes specially the ones located at high-risk area. Hence, three main cost components are considered in this case study. The first component is the cost to transport groundwater from new to existing EWF nodes. The second component is the cost associated with pumping groundwater to the surface, and the last component is the cost of desalinating pumped water having certain groundwater salinity. The decision variables comprise of 3 parameters, including the transportation (1 decision



(a) (b)

Fig. 2. Location of existing nodes located at high-risk area.

variable) and the groundwater (2 decision variables) parts, which are elaborated below. The optimal decisions of the selected variables will minimise the operating cost of the new node locating at the optimal location and overall risk of existing nodes. The mathematical formulation for the optimisation model is presented in the following section, where spatial (distance) and economic related data are used to run the optimisation model, along with weights associated with each risk factor is described in Appendix E.

Since the optimisation process involves many decision variables and various calculation steps; then, a computer model such as Excel-based Binary Linear Programming Solver is valuable in performing these steps, and to solve the optimisation formulation by ensuring that all functions and variables are sufficiently expressed, including the binary constraint on the decision variables. As for the spatial and temporal scales, the model developed will vary under various geographical characteristics and will differ over different seasons. In this study, the optimisation model is applied for hydroponic greenhouses distributed within the State of Qatar for Summer season data.

2.2.2. 1Mathematical formulation

The following model formulation provides the basis for optimisation, and the description of each can be found in Appendix D.

$$\boldsymbol{Min} \left\{ \sum_{i=1}^{100} \sum_{j=1}^{n} d_{ij} C_T x_i + \sum_{i=1}^{100} Dp_i C_P x_i + \sum_{i=1}^{100} S_i C_D x_i \right\} \quad (1)$$

s.t.

$$\sum_{i=1}^{100} x_i \left(w_s S_i + w_{ph} pH_i + w_{rr} RR_i + w_d Dp_i + w_t T_i + w_h H_i + w_{sr} SR_i \right) \le Cn_1 \quad (2)$$

$$\sum_{i=1}^{100} x_i \left(w_s S_i + w_{ph} pH_i + w_{rr} RR_i + w_d Dp_i \right) + w_t T_1 + w_h H_1 + w_{sr} SR_1 \le Cn_2 \quad (3)$$

$$\sum_{i=1}^{100} x_i \left(w_s S_i + w_{ph} pH_i + w_{rr} RR_i + w_d Dp_i \right) + w_t T_2 + w_h H_2 + w_{sr} SR_2 \le Cn_3 \quad (4)$$

$$\sum_{i=1}^{100} x_i \left(w_s S_i + w_{ph} pH_i + w_{rr} RR_i + w_d Dp_i \right) + w_t T_3 + w_h H_3 + w_{sr} SR_3 \le Cn_4 \quad (5)$$

$$\sum_{i=1}^{100} x_i = 1 \quad (6)$$

$$d_{ij},\ Dp_i,\ S_i,\ x_i \ge 0 \quad (7)$$

where, Eq. (1) is the total operating cost objective function based on inter-nodal distance and groundwater characteristics for the new EWF node that will supply the required water demands to the existing EWF nodes; Eq. (2) constrains the new EWF node location in order to select a low risk location with an AHP value less than 22 and 194, for dairy and fodder node scenarios, respectively; Eq. (3) constrains the new EWF node location such that it would minimise the risks for the existing nodes - thus, reducing high AHP value of ‘Al Safwa Farm’ node to a value less than 28.91; Eq. (4) constraints the new EWF node location such that it would minimise the risks for the existing nodes - thus, reducing high AHP value of ‘Global Farm’ node to a value less than 22.60; Eq. (5) constraints the new EWF node location such that it would minimise the risks for the existing node - thus, reducing high AHP value of AGRICO Farm to a value less than 24.29; Eq. (6) ensures the selection of a single location for the new EWF node; and Eq. (7) ensures that all decision variables must be non-negative. Additionally, the right-hand side of the constraints (Cn) are calculated as the composite risk indicator, based on the AHP method, that represents the risk level of the existing nodes.

Table 4
Desalination costs for RO desalination process for various capacities **Loutatidou & Arafat (2015)**.

Reverse Osmosis (RO) – Brackish Water	
Capacity of desalination plan (m^3/day)	**Desalination cost (US $/$m^3$)**
Less than 20	5.63 – 12.9
20 - 1200	0.78 – 1.33
40,000 – 46,000	0.26 – 0.54

2.2.3. Optimisation model data and parameters

The optimisation begins with initialisation of the database, including the distance and cost matrix between new and existing EWF nodes, the groundwater salinity value and cost associated to desalinate such salinity level, in addition to the groundwater depth value along with the cost associated with pumping groundwater. It is then followed by the simulation steps to calculate the operating cost of the initial data. If there is a possibility to improve the results, it will automatically alter the model parameters (d_{ij}, Dp_i, S_i) and decision variables (x_i) and recalculate the objective functions (operational cost). The calculation process within optimisation module will be iterated through changing the decision variables (x_i) until the minimum (optimal) operational costs are obtained. As per Loutatidou & Arafat (2015), desalination costs depend on several factors that comprise the desalination process, energy source, operation and maintenance costs. Table 4 illustrates the desalination cost for RO desalination processes at different capacities. In general, desalination costs decrease with increasing capacity.

The calculation for the new RO desalination plant capacity was based on the estimated water requirements and consumption by dairy cattle as summarised in Appendix G by Ministry of Agriculture Food and Rural Affairs (2019), and by assuming that approximately around 15% of the milking-age cows presented on a dairy farm could be considered dry cows. Moreover, the water consumed daily by different categories of sheep range from 4.0-11.4 L/day.

At the time of writing, Baladna consists of 10,000 Milking Cows, 5,000 Goats, and 40,000 Awassi Sheep, in addition to the 4,000 new cattle that were further introduced to the Baladna farm i (Schroeder, 2017). Al Rawdah dairy farmhouses around 4000 Holstein Friesian cows (Almahadairy, 2014), and Ghadeer dairy farm has a capacity of 2000 heads of Holstein cows (Ghadeerdairy, 2020). Thus, the total water requirements for the three dairy farms will range from 2,698,000 to 3,409,000 L/day (2698-3409 m^3/day). For the Rhodes/Fodder farms, studies showed that Rhodes consumes high amounts of water for its production ranging from 35,000 – 45,000 m^3/ha/year (Patil et al., 2014). Hence the overall approximate water consumption for the four fodder farms based on their estimated farm size is summarized in Table 5.

According to the Annual UAE Food Industry Report (2017), Rhodes grasses are excellent alternatives for sustainable forage production in salt-affected areas which can be integrated in a forage–livestock systems, especially in environments with a low soil quality and limited water resources. Thus, the new RO plant will be only based on the water consumed by dairy farms with an approximate unit size of 4,000 m3/day, in order to satisfy the three existing dairy farm water requirements. However, by considering new EWF node water requirements satisfaction, the total capacity of the new RO plant is assumed to be 14,000 m^3/day.

Desalination of brackish water requires large quantities of energy, where often the energy input is based on fossil fuels. The consumption of electrical energy for RO desalination with a unit size of 14,000 m^3/day is nearly 2.10 kWh/m^3 for brackish water with a salinity of approximately 5000 ppm (Manju & Sagar, 2017). Noting that the groundwater salinity in Qatar varies between 2206.12 and 5639.81 ppm, and the subsequent energy required in order to desalinate using RO desalination will range from 0.93 to 2.37 kWh/m^3. Hence, the cost of desalinating groundwater using RO desalination process is approximately between 1467.12 $ and 9588 $, as illustrated in Table 4; where the rate associated with electricity consumption for productive farms in the State of Qatar is 1.68 QAR/kWh (0.46 $/kWh) (KAHRAMAA, 2020).

The other cost component in the objective function is the transportation cost. A previous study demonstrated that approximate cost is 0.061 $/$m^3$ per 100 km to transport water, thus it is equivalents to 0.00061 $/$m^3$/km (Zhou & Tol, 2005). The distance between the new node (i) and existing node (j) is calculated using the following Distance Formula:

$$d = \sqrt{\left(x\ coordinate_j - x\ coordinate_i\right)^2 + \left(y\ coordinate_j - y\ coordinate_i\right)^2}$$

Therefore, using the Distance Matrix, the total cost required to transport groundwater from new to an existing node is generated (Appendix E). Lastly, the operating cost of lifting groundwater to the surface using an electrical motor is 0.1780 $/kWh, where 2.725 kWh is required for pumping groundwater per each meter (Robinson, 2002). Thus, the groundwater pumping costs at various locations for dairy farms are illustrated in Appendix F. The same procedures are applied for fodder farms. Ultimately, all the previous data for the minimisation of the objective function and set of constraints required to perform and solve binary optimisation model are achieved by using Excel-based Binary Linear Programming Solver linear.

3. Results and discussion

The methodology presented in this study is applied to a case study that encompasses dairy farms, fodder farms and the combination of both farms in Qatar. Nine risk factors comprising from weather, soil and groundwater factors were selected to perform the AHP method for fodder and mix nodes. However, the soil factors are eliminated from the analysis in the case of dairy node, as the soil does not have any impact on animals nor dairies. Thus, the results in the below sections will cover and demonstrate the two main study's outcomes, including composite indicators and the liner optimisation for the three nodes types

3.1. Composite risk indicator

Based on the results summarised in Table 8, temperature and groundwater quality have the highest impact on dairy farm, with

Table 5
Water consumption for the four fodder farms.

Fodder Farm	Area (ha)	Water consumption (m^3/yr.)	Water consumption (m^3/day)
Irkhaya	1102	38,570,000 - 49,590,000	105,671 - 135,863
Hassad Qatar	1122	39,270,000 -50,490,000	107,589 - 138,329
Al Dawoudiya	1139	39,865,000 - 51,255,000	109,219 - 140,425
Mazzraty	356	12,460,000 - 16,020,000	34,137 - 43,890
Total Water Consumption		**130,165,000 - 167,355,000**	**356,616 - 458,507**

Table 6
Relative weight and importance percentage of five risk factors on a dairy farm.

Ranking	Factor	Principal Eigen Vector (Weight)	Importance Percentage
1	Temperature	0.21638	21.638%
2	Groundwater Salinity	0.21229	21.229%
2	Groundwater pH	0.21229	21.229%
3	Groundwater Depth	0.19238	19.238%
4	Solar Radiation	0.09693	9.693%
5	Humidity	0.06974	6.974%

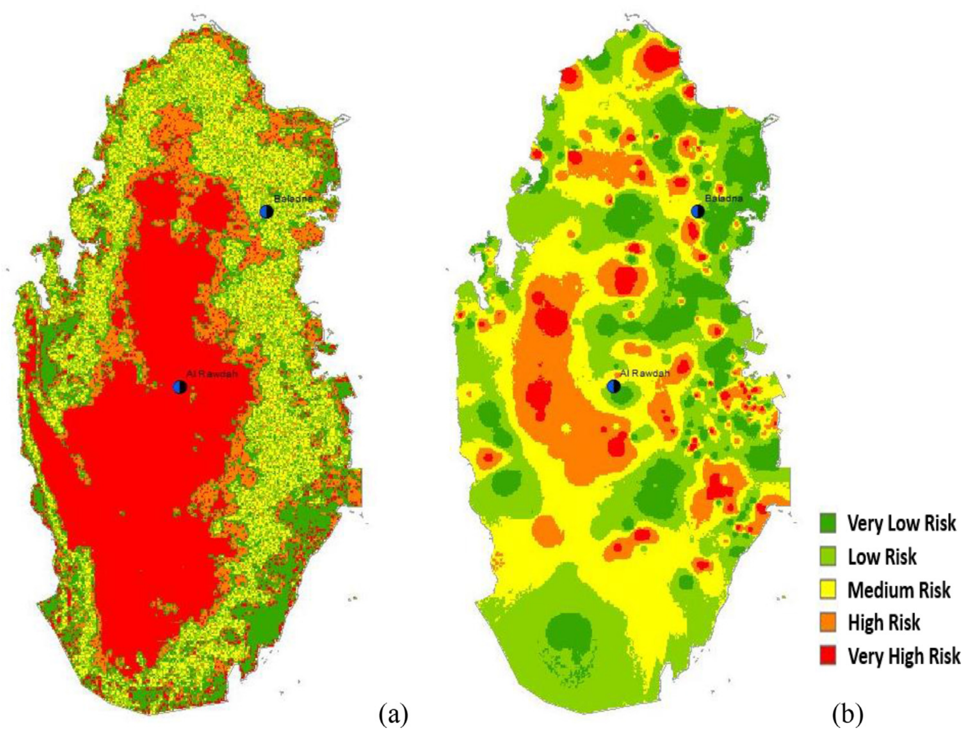


Fig. 3. Location of combined farms in the State of Qatar on the (a) dairy and (b) fodder geospatial risk map.

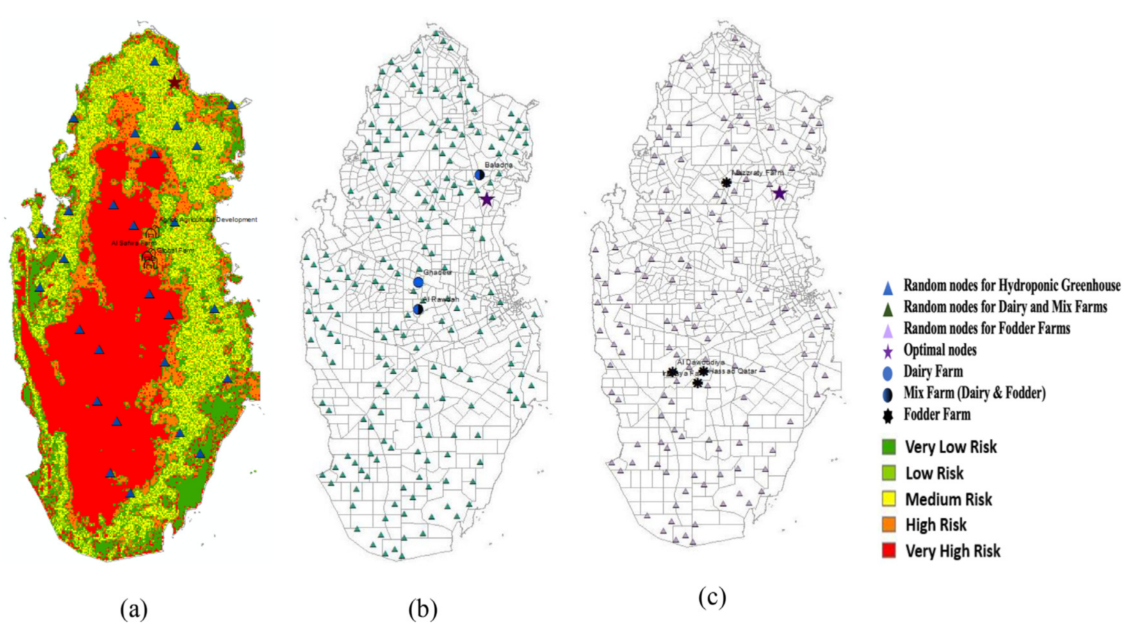


Fig. 4. The location of selected EWF node (optimal) corresponding to (a) 28 potential nodes (b) and (c) 100 potential nodes

Table 7
comparison of AHP risk value for existing nodes before and after the application of optimisation.

EWF Node	AHP Risk Value (Summer) before Optimisation	AHP Risk Value (Summer) after Optimisation
Hydroponic Greenhouse		
New EWF Node	-	13.09390 (very low)
Al Safwa Farm	28.9100 (very high)	10.1194 (very low)
Global Farm	22.6039 (high)	10.10737 (very low)
Agrico Farm	24.2957 (high)	10.01826 (very low)
Dairy and Mix Nodes		
New EWF Node	-	21 (low)
Ghadeer Dairy	33 (very high)	17.308 (very low)
Al Rawdah Dairy	35 (very high)	14.529 (very low)
Fodder Nodes		
New EWF Node	-	80 (very low)
Irkhaya Farm	205 (medium)	16.817 (very low)
Hassad Qatar	230 (medium)	16.820 (very low)
Al Dawoudiya	239 (medium)	16.811 (very low)

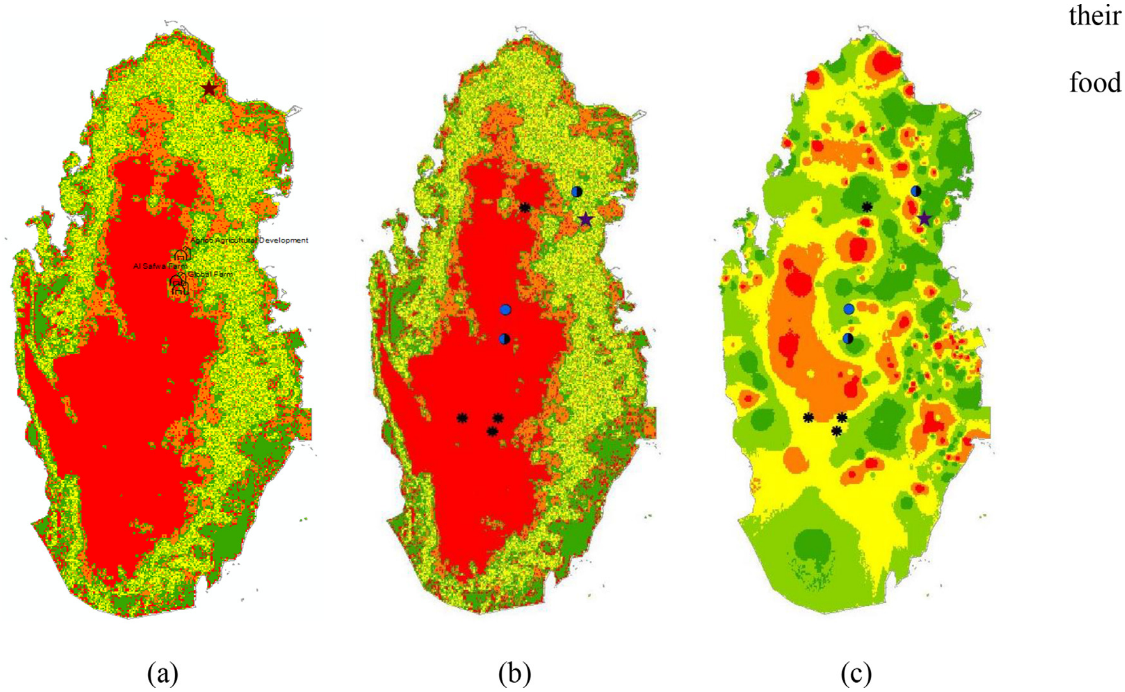


Fig. 5. The optimal location of proposed EWF node with respect to (a) hydroponic greenhouse map (b) dairy risk map and (c) fodder risk map.

a percentage of 21.6% and 21.2% respectively. These results indicate that having a facility that is not fully controlled for breeding the dairy livestock, will be exposed to a reduction in the feed intake, milk production and livestock fertility, which is mainly due to the harsh weather conditions and high heat stress. In dairy farming, where the ambient temperature and humidity goes above animal specific thresholds, heat stress in cows will occur. It is well known that lactating cows initially respond to slight heat stress through sweating, panting, drinking more, and seeking shade when possible. Thus, cows at higher temperatures eat less feed, which in turn will lead to a reduction within milk production. Consequently, it's essential to use a modelled temperature projection when planning new structures, enhance the cooling capacity of existing barns or even adapts simple methods, such as the providing shade and install fans along with water misting systems to protect the welfare of the animals and minimise the economic losses from heat stress. However, in terms of water quality, dairy cattle need free access to quality and clean water source for optimal milk production. Generally, water salinity below 3,000 ppm is considered safe for dairy cows, though its preferable to have water salinity below 1000 ppm to avoid any possible temporary diarrhoea to the cows and animals (National Research Council, 2001).

In the case of fodder in Qatar, since they are grown and produced on an open field, it will be exposed to harsh weather conditions and will have a high risk of losing the harvest, whichmakes it more challenging in managing the risk of weaker yield. However, in combined farms, groundwater and soil quality factors have the highest impact on this type of farming. A study by the National Research Council (2001) proved that the excessive minerals in water can affect the availability of other dietary nutrients, which can contribute to digestive, health and performance problems. As such, the maximum acceptable concentration of Arsenic (As) is 0.05 ppm for cows. The ranks associated with all the risk factors that have the highest impact on fodder and combined farms are illustrated in Appendix B.

The final step in the implementation of the composite indicator is to validate assumptions made during the AHP method. This can be achieved by calculating the Consistency Index (CI) and Consistency Ratio (CR) for dairy, fodder and combined farms. In this study, the CR is estimated to be 4.7%, 2.0% and 5.2% respectively. Based on the literature, the CR should be less than 10%, hence all assumptions made validated the literature and the inconsistency within our subjective judgments is acceptable.

When overlaying the locations of the two combined farms on the dairy and fodder risk maps as shown in Fig. 3, the following can be realized; the fodder part inside Baladna and Al Rawdha farms are expected to be located in low-risk areas (green areas) which could be due to the accepted groundwater quality level at those locations. However, the dairy part in Al Rawdah farm will be situated in a high-risk area (red areas), this is mainly due to the fact that Al Rawdah farm is located in the center of Qatar with a higher temperature, which will have an impact on the dairy milk production. Eventually, this comparison demonstrates that it is highly essential to consider and balance all factors when having combined farms.

3.2. Geospatial optimisation model application

Finally, a simple linear optimisation is conducted to determine the optimal location for the new EWF node to be allocated and established. Noting that the chosen/optimal location will minimise the risk of existing EWF nodes whilst operating at minimal operating costs. Hence, in this study, two scenarios will be conducted to illustrate the feasibility and capability of the geospatial optimisation model to be applied on various food systems. The first scenario is the hydroponic greenhouses, and the geospatial risk map is taken from recent work reported by Haji et al. (2020). The second scenario is our current dairy and fodder farms, where both cases represent the Food Nexus, and water is the core factor that affects the overall efficiency and AHP risk level. Thus, the objective of the optimisation is to identify a location for new EWF nodes, with better water quality; in order to reduce the operational cost, such as the cost of pumping and desalinating groundwater, and hence supply good water quality to existing EWF node to reduce their overall risk. Fig. 4 (a) illustrates the optimal node with respect to 28 potential nodes, while Fig. 4 (b) and (c) with respect to 100 potential nodes. Although the potential EWF nodes are distributed randomly, including high-risk areas, the four constraints assigned to the optimisation model contributed to enhancing its ability to select optimal EWF nodes located at low-risk areas with better groundwater quality.

Moreover, outcomes from the linear programming optimisation validated the trade-offs between cost components. Though, the location of the new node (north-east) for both scenarios is slightly far from most of the existing nodes, which implies a larger transportation cost. However, the location with better groundwater salinity and less depth is selected. Hence, the results summarised in Table 7 demonstrates that through the allocation of a new node in an optimal location (Fig. 4) the risk of existing nodes decreased tremendously. Initially, Ghadeer dairy, Al Rawdah dairy, Al Sawfa farm, Global farm and Agrico farm are located in very high- and high- risk areas, where Irkhaya, Hassad Qatar and Al Dawoudiya fodder farms are located in slightly less risk areas in which all of them indicating poor water qualities with an AHP risk value of 28, 22, 24 and 33, 35 and 205, 230, 239 for hydroponic greenhouse, dairy and fodder farms respectively. However, with the allocation of a new EWF nexus node to be the main source of water supply, the risk level reduces tremendously to approximately less than 17 for all eight existing nodes. Therefore, the optimisation result proves the necessity to use groundwater with improved qualities within EWF nodes.

4. Conclusion

Farming systems are threatened by a large number of environmental, social, economic and institutional problems. Qatar and many other countries worldwide are intensifying their food production as a driver for achieving food security. Accordingly, the nexus approach to efficiently manage various resource become highly essential especially due to the increase in resource uncertainties across energy, water and food sectors. Thus, the enhanced EWF nexus nodal method was applied to represent various farming industries having different characteristics. The study implemented a simple linear optimisation model for the sake of introducing a new EWF node that will reduce the AHP risk level of existing EWF nodes. The study considered both dairy and fodder farms in Qatar, and the generated composite geospatial risk indicator map demonstrated that five out of seven EWF nodes are located at medium to high-risk areas. The objective function of the optimisation model accounts for three cost components; the cost of groundwater transportation, pumping and desalination. Hence, by running the optimisation model into an Excel-based Binary Linear Programming Solver, a location in the north-east of Qatar was selected as an optimal location in order to allocate the new EWF node, which will operate at the least cost and at the same time reduces the AHP risk of five existing nodes. In conclusion, this study provides a promising approach for defining nodes that perform better under methodological risk, hence opening up the way for deeper decision-making with the view to lower the effect of risk factors, thus improving the resilience of EWF systems.Future work should evaluate various node categories, by including other industries, for example: energy centric or water centric system, and analyse nodes with different performance metrics, e.g. cost. In addition, improve the geospatial optimisation model illustrated in the current study to include further uncertainties and limitations such as climatic conditions. Also, enhance the optimisation model to reflect all EWF related costs and emissions in Qatar. Finally, perform a sensitivity analysis study to measure the impact of fluctuations in optimisation model parameters on the performance of the overall EWF node.Figs. 5, 6

Declaration of Competing Interest

None

Acknowledgment

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Appendix A. Thomas Saaty's values used in AHP method development

Table A1, A2

Table A1
Pairwise comparison matrix for Fodder Farm of the nine risk factors.

C_jC_i	Temperature	Humidity	Solar Radiation	Soil Quality (As)	Soil Quality (Fe)	Groundwater Depth	Groundwater Recharge Rate	Groundwater Salinity	Groundwater pH
Temperature	1.00	2.00	1.50	1.50	3.00	2.00	3.00	1.50	2.00
Humidity	0.50	1.00	0.50	0.50	3.00	0.67	3.00	0.50	0.50
Solar Radiation	0.67	2.00	1.00	2.00	3.00	2.00	3.00	2.00	2.00
Soil Quality (As)	0.67	2.00	0.50	1.00	3.00	1.50	3.00	1.00	1.00
Soil Quality (Fe)	0.33	0.33	0.33	0.33	1.00	0.33	1.00	0.33	0.33
Groundwater Depth	0.50	1.50	0.50	0.67	3.00	1.00	3.00	0.80	0.80
Groundwater Recharge Rate	0.33	0.33	0.33	0.33	1.00	0.33	1.00	0.33	0.33
Groundwater Salinity	0.67	2.00	0.50	1.00	3.00	1.25	3.00	1.00	1.00
Groundwater pH	0.50	2.00	0.50	1.00	3.00	1.25	3.00	1.00	1.00
Sum	5.17	13.17	5.67	8.33	23.00	10.33	23.00	8.47	8.97

Table A2
Pairwise comparison matrix for Combined Farm of the nine risk factors.

C_jC_i	Temperature	Humidity	Solar Radiation	Soil Quality (As)	Soil Quality (Fe)	Groundwater Depth	Groundwater Recharge Rate	Groundwater Salinity	Groundwater pH
Temperature	1.00	2.00	1.50	0.50	3.00	0.50	3.00	0.50	0.40
Humidity	0.50	1.00	0.33	0.33	3.00	0.50	3.00	0.33	0.50
Solar Radiation	0.67	3.00	1.00	0.33	3.00	0.50	3.00	0.33	0.50
Soil Quality (As)	2.00	3.00	3.00	1.00	3.00	0.50	3.00	0.67	0.50
Soil Quality (Fe)	0.33	0.33	0.33	0.33	1.00	0.33	1.00	0.33	0.33
Groundwater Depth	2.00	2.00	2.00	2.00	3.00	1.00	3.00	0.50	0.80
Groundwater Recharge Rate	0.33	0.33	0.33	0.33	1.00	0.33	1.00	0.33	0.33
Groundwater Salinity	2.00	3.00	3.00	1.50	3.00	2.00	3.00	1.00	1.25
Groundwater pH	2.50	2.00	2.00	2.00	3.00	1.25	3.00	0.80	1.00
Sum	11.33	16.67	13.50	8.33	23.00	6.92	23.00	4.80	5.62

Appendix B. Relative weight and importance percentage generated from AHP method

Table B1, B2

Table B1
Relative weight and importance percentage of nine risk factors in a fodder farm.

Ranking	Factor	Principal Eigen Vector (Weight)	Importance Percentage
1	Temperature	0.18275	18.275%
2	Solar Radiation	0.17901	17.901%
3	Soil Quality (As)	0.12498	12.498%
4	Groundwater Salinity	0.12229	12.229%
5	Groundwater pH	0.11871	11.871%
6	Groundwater Depth	0.10225	10.225%
7	Humidity	0.08457	8.457%
8	Groundwater Recharge Rate	0.04271	4.271%
8	Soil Quality (Fe)	0.04271	4.271%

Table B2
Relative weight and importance percentage of nine risk factors in a combined farm.

Ranking	Factor	Principal Eigen Vector (Weight)	Importance Percentage
1	Groundwater Salinity	0.19329	19.329%
2	Groundwater pH	0.16834	16.834%
3	Groundwater Depth	0.14852	14.852%
4	Soil Quality (As)	0.13997	13.997%
5	Temperature	0.09865	9.865%
6	Solar Radiation	0.09384	9.384%
7	Humidity	0.07338	7.338%
8	Groundwater Recharge Rate	0.04200	4.200%
8	Soil Quality (Fe)	0.04200	4.200%

Appendix C. The three main steps to generate output map for optimisation application

Fig. 6

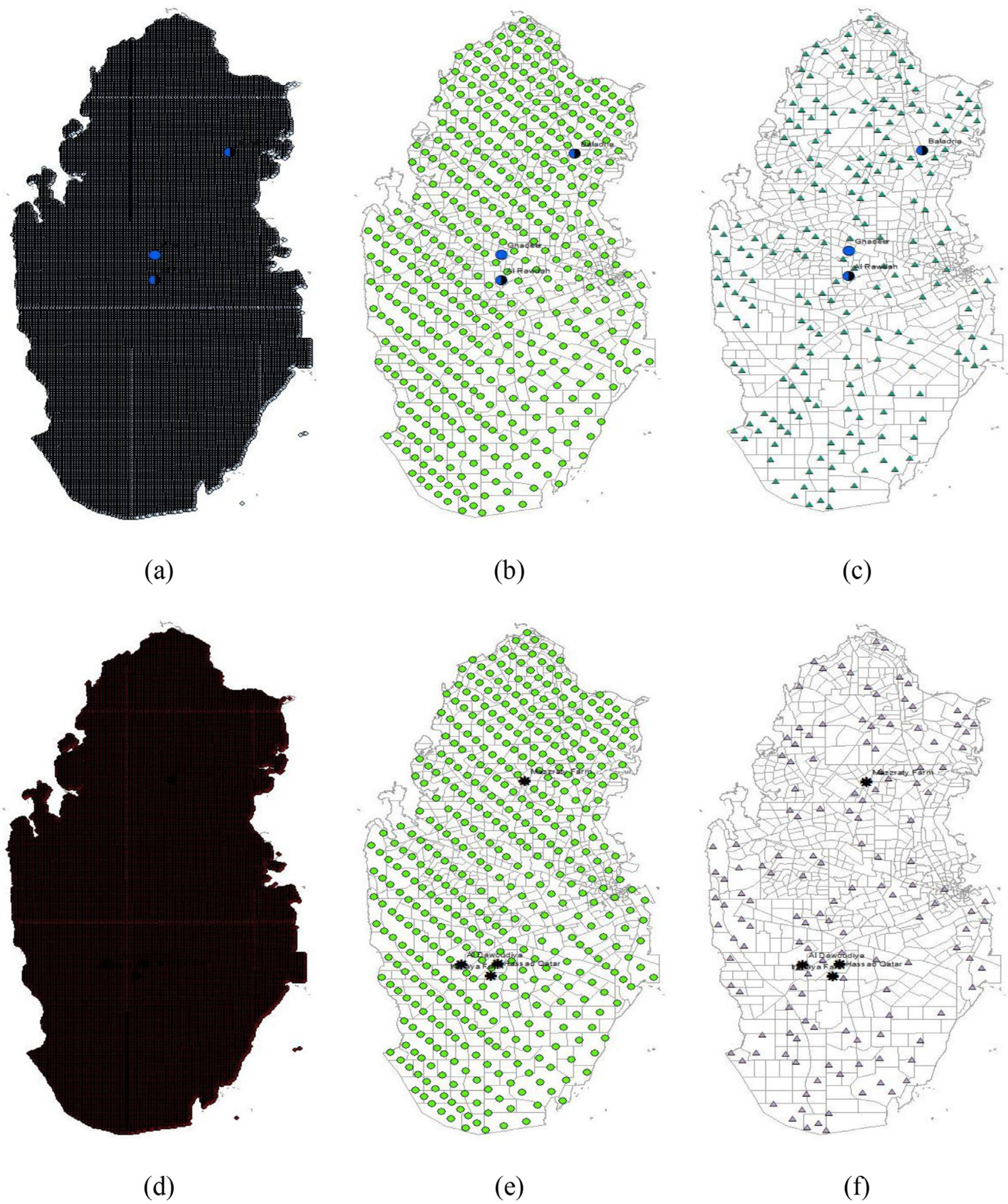

Fig. 6. The raster map for (a) dairy farm (d) fodder farm, the location of random nodes for (b) dairy farm (e) fodder farm and candidate nodes (c) dairy farm (f) fodder farm.

Appendix D. Decision variables and parameters used in optimisation method

Table D1, D2

Table D1
The decision variables of the optimisation objective function

Index	Description
d_{ij}	*distance between i and j*
Dp_i	*level of groundwater depth at location i*
S_i	*salinity amount at location i*
x_i	$1 =$ *when (new node) is established at location i*
	$0 =$ *otherwise*

Table D2
All the parameters used in the optimisation

Index	Description
i	*new (proposed) node*; where $i = 1, 2, \ldots, 100$
j	*Exisiting node*; where $j = 1, 2, \ldots, 5$ for Ghadeer, Al Rawdah, Irkhaya, Hassad Qatar, Al Dawoudiya respectivily
T_i	*temperature at location i*
H_i	*humidity level at location i*
SR_i	*solar radiation at location i*
RR_i	*recharge rate at location i*
pH_i	*pH level at location i*
C_T	*cost of transporting water from i to j*
C_P	*cost of pumping groundwater at location i*
C_D	*cost of desalinating groundwater with i location salinity*
w_s	*relative importance weight generated from AHP*
w_{ph}	*relative importance weight generated from AHP method for groundwater pH*
w_d	*relative importance weight generated from AHP method for groundwater depth*
w_{rr}	*relative importance weight generated from AHP method for recharge rate*
w_t	*relative importance weight generated from AHP method for temperature*
w_h	*relative importance weight generated from AHP method for humidity*
w_{sr}	*relative importance weight generated from AHP method for solar radiation*

Appendix E. Decision variables and parameters used in optimisation method

Table E1, E2

Table E1
The distance (a sample of 20 points) associated with transporting groundwater from the new node (i) to an existing node (j).

ij	1	2	3	4	5
1	86.9347912	78.7853433	51.6971972	55.5333318	55.9106278
2	84.7271614	76.6648385	51.5179018	55.5181389	54.6787101
3	81.4074954	73.1903039	45.8891728	49.9474051	48.6683
4	81.2412066	73.1318951	46.6524243	50.8290873	47.5819689
5	75.8266365	67.7063836	40.4546677	44.5045832	43.4529115
6	74.6586957	66.442183	38.7922239	41.6748065	46.355628
7	73.5637476	65.3511128	41.7487049	44.0439286	50.2843644
8	71.8988384	63.7619499	33.021192	36.6903103	38.4802371
9	74.5835835	66.8208163	29.9707505	33.8262506	34.6854464
10	68.1613059	59.9286389	36.9112515	38.736153	46.0736004
11	65.3511128	57.1452615	31.142669	33.7868709	39.309
12	70.9885242	63.709112	40.1206097	43.9945771	36.4699268
13	63.7014695	55.5849844	34.7278286	38.779508	32.6583521
14	61.7724346	53.5364092	34.3219768	35.4765288	44.0424359
15	64.0787719	56.2367291	23.6091248	27.7943741	24.7538316
16	70.2562038	63.234343	29.1384668	33.0911108	26.4534818
17	66.8627341	59.4413423	24.33414	26.4720188	33.3589948
18	61.6633702	54.0988624	18.8007559	22.2018184	25.8750002
19	58.1180461	50.2048117	18.1135343	22.261716	21.2964522
20	60.635436	53.2726204	17.0903766	21.2734024	18.7522682

Table E2
The cost (a sample of 20 points) associated with groundwater transportation from the new node (i) to an existing node (j).

ij	1	2	3	4	5
1	530.302226	480.590594	315.352903	338.753324	341.05483
2	516.835684	467.655515	314.259201	338.660647	333.540131
3	496.585722	446.460854	279.923954	304.679171	296.87663
4	495.57136	446.10456	284.579788	310.057432	290.25001
5	462.542483	413.00894	246.773473	271.477958	265.06276
6	455.418044	405.297316	236.632566	254.216319	282.769331
7	448.73886	398.641788	254.6671	268.667965	306.734623
8	438.582914	388.947895	201.429271	223.810893	234.729446
9	454.95986	407.60698	182.821578	206.340129	211.581223
10	415.783966	365.564697	225.158634	236.290534	281.048962
11	398.641788	348.586095	189.970281	206.099913	239.7849
12	433.029998	388.625583	244.735719	268.36692	222.466553
13	388.578964	339.068405	211.839754	236.554999	199.215948
14	376.811851	326.572096	209.364058	216.406826	268.658859
15	390.880508	343.044047	144.015661	169.545682	150.998373
16	428.562843	385.729493	177.744648	201.855776	161.366239
17	407.862678	362.592188	148.438254	161.479315	203.489869
18	376.146558	330.003061	114.684611	135.431092	157.837501
19	354.520081	306.249351	110.492559	135.796467	129.908359
20	369.876159	324.962984	104.251297	129.767755	114.388836

Appendix F. Associated cost used in optimisation method

Table F1

Table F1
Economic (a sample of 20 points for cost-related) data used to run the optimisation model for dairy farm.

Xi	Xj	X Coordinate	Y Coordinate	GW Salinity (ppm)	GW pH	GW Depth (m)	Pumping GW Cost ($)	GW Salinity (ppm)	Energy consumption using RO (kWh/m3)	Desalination Cost ($)	AHP Risk Value
0	1	51.062187	24.494057	0.314494	7.81853	67	32.49835	3144.94	1.3208748	2981.480491	26
0	2	51.017263	24.524006	0.315238	7.81791	10.7	5.190035	3152.38	1.3239996	2995.603783	15
0	3	51.129574	24.542725	0.314859	7.81886	58.6	28.42393	3148.59	1.3224078	2988.405086	25
0	4	51.047212	24.553956	0.315735	7.81786	88.9	43.120945	3157.35	1.326087	3005.056886	30
0	5	51.062187	24.606368	0.316986	7.81738	104.8	50.83324	3169.86	1.3313412	3028.917236	33
0	6	51.230654	24.610112	0.314805	7.81992	100.9	48.941545	3148.05	1.322181	2987.380119	33
0	7	51.129574	24.621343	0.3168	7.81812	95.6	46.37078	3168	1.33056	3025.363683	32
0	8	51.28681	24.643805	0.314118	7.82092	16.8	8.14884	3141.18	1.3192956	2974.355607	17
0	9	50.946132	24.647549	0.318087	7.81572	14.7	7.130235	3180.87	1.3359654	3049.994693	16
0	10	51.163268	24.673755	0.318108	7.81803	112.7	54.665135	3181.08	1.3360536	3050.397425	35
0	11	51.129574	24.703705	0.319716	7.81689	104.5	50.687725	3197.16	1.3428072	3081.314197	33
0	12	50.867514	24.71868	0.319004	7.81418	74.4	36.08772	3190.04	1.3398168	3067.605451	28
0	13	51.283066	24.726167	0.316342	7.82074	5.1	2.473755	3163.42	1.3286364	3016.622426	14
0	14	51.18573	24.737398	0.3203	7.81765	112.5	54.568125	3203	1.34526	3092.581266	35
0	15	50.998544	24.741142	0.321428	7.81395	108.1	52.433905	3214.28	1.3499976	3114.401898	34
0	16	50.833821	24.744886	0.319051	7.81374	13.7	6.645185	3190.51	1.3400142	3068.50944	16
0	17	50.908695	24.744886	0.320272	7.81358	70.8	34.34154	3202.72	1.3451424	3092.040594	27
0	18	50.95362	24.782323	0.322167	7.81255	92.6	44.91563	3221.67	1.3531014	3128.739098	31
0	19	51.032238	24.793554	0.324156	7.81252	110	53.3555	3241.56	1.3614552	3167.490876	34

Appendix G. Water requirement and consumption per different cattle types

Table G1

Table G1
Water Consumption by Dairy Cattle.

Dairy Cattle Type	AverageMilk Production (kg milk/day)	Water Requirement Range(L/day)	Average Typical Water Use(L/day)
Dairy calves (1-4 months)	-	4.9-13.2	9
Dairy heifers (5-24 months)	-	14.4-36.3	25
Milking cows	45.5	132-155	115
Dry cows	-	34-49	41

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