



Implications of Spatial Variability of Soil Physical Attributes in Delineating Site-Specific Irrigation Management Zones for Rice Crop

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Received: 27 May 2023 / Accepted: 3 October 2023 / Published online: 23 October 2023
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Abstract

The primary objective of this study was to investigate the spatial variability of soil physical attributes and subsequently delineate site-specific management zones for irrigated rice cultivation in Guilan province, Iran. By achieving this objective, the study aims to determine crop evapotranspiration to schedule irrigation practices more precisely and optimize water usage in Guilan province, Iran. A total of 120 soil samples were collected from within the study area to measure the soil physical and hydraulic properties. Additionally, meteorological data were acquired from four weather stations across the study area, and the Penman-Monteith method was used to estimate the reference potential evapotranspiration. To determine the standard crop evapotranspiration, crop coefficients were applied. Spatial variability of soil properties and gross irrigation water requirements were analyzed using geostatistical techniques, and spatial distribution maps were constructed in order to determine irrigation management zones using fuzzy k-means clustering algorithm. The estimated standard crop evapotranspiration varied from 572 to 597 mm. In terms of gross irrigation water requirements, a significant variability emerged, ranging from 710 to 1082 mm. Utilizing the geostatistical techniques and the fuzzy k-means clustering algorithm, the study successfully identified four distinct irrigation management zones. Irrigation management zone 1 was characterized by regions with lower gross irrigation water requirements and commendably high water productivity. Conversely, irrigation management zone 4 encompassed areas with relatively lower water productivity and higher gross irrigation water needs. The results underscore the effectiveness of site-specific irrigation management within the studied paddy fields and highlight the necessity for tailored irrigation strategies to enhance water efficiency and productivity.

Keywords Fuzzy k-means clustering algorithm · Fuzzy performance index · Gross irrigation water requirement · Irrigation management zone · Net irrigation water requirement · Spatial variability

1 Introduction

The soil hydro-physical properties play a crucial role in achieving efficient and effective irrigation practices. However, the challenge arises when dealing with the spatial variability of soil properties, particularly at a substantial regional scale. In water-scarce areas, knowledge of the variability of soil physical properties, such as saturated hydraulic conductivity, is important for water conservation and increasing water use efficiencies (Shukla and Sharma 2023). This variability often becomes too pronounced to be effectively managed through uniform irrigation water application. Although most of the physical and hydraulic attributes of soil that contribute to determining irrigation requirement are well recognized, practical limitations such as high costs, technical challenges, and time constraints hinder the

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accurate determination of these attributes at the necessary spatial resolutions for site-specific irrigation management (Oliveria 2003).

The adequacy of the applied water to fulfill the standard crop evapotranspiration is the first step towards enhancing water productivity in field management. This emphasizes the critical need for accurate estimates of gross irrigation water requirements (GIWR). GIWR represents the depth of water that must be supplied by irrigation to fulfill evapotranspiration and leaching water requirements, excluding the utilization of stored water in the soil and precipitation (Jensen et al. 1990). Therefore, to calculate GIWR, a fundamental component is the estimation of crop evapotranspiration (ET_c). A widely used reference for determining GIWR globally is the FAO-56 manual (Allen et al. 1998).

The spatial variability of soil attributes significantly contributes to the varying irrigation requirements across agricultural fields. This divergence arises due to a multitude of factors, including physiographic units, soil type, climatic conditions, effective rainfall, growth stage of plants, cultivation techniques, and more. Furthermore, the water demand of crops is not uniformly distributed throughout the entire growing season (Azevedo et al. 2007). Therefore, irrigation requirements may differ among different areas of a particular field. Although different irrigation systems have been developed, most irrigation methods continue to apply a uniform amount of water across the entirety of a field. This approach overlooks the intricate spatial variability of soil attributes (Al-Karadsheh et al. 2002).

In conventional uniform irrigation management, the focus is placed on applying water uniformly in terms of depth and timing, based on the average values of crop response to evapotranspiration and irrigation water. Therefore, this approach disregards the spatial variability inherent in how crops respond to water availability. Consequently, it can lead to both deficit and excess water use, as well as suboptimal economic returns in certain field areas (King et al. 2006). To address these challenges and ensure effective water managements, distinct water management strategies are needed across large-scale fields that account for heterogeneity of soil attributes and resulting variations in crop water requirement (Oliveria 2003).

Spatial variability of soil properties pertaining to irrigation management can be effectively addressed through the implementation of site-specific management strategies (Aggag and Alharbi 2022). Its emphasis is the importance of site-specific management for long-term crop productivity and, as a result, reducing environmental hazards caused by uneven fertilizers and water applications. This approach involves segmenting a large field into smaller units known as management zones (MZ) (Zhang et al. 2002). These zones are characterized by greater homogeneity in terms of specific properties of interest compared to the entire field.

Each MZ is an area where input application rates of factors that limit yield can be strategically managed to optimize inputs and enhance yield potential. Maftukhah et al. (2022) reaffirmed the necessity of adapting management strategies based on the prevailing site conditions to achieve optimal outcomes. Mzuku et al. (2005) demonstrated the significant spatial variability of soil physical properties across production fields. Utilizing site-specific management zones offers a viable solution to effectively manage the in-field variability of soil physical properties that influence crop growth and yield. However, Létourneau and Caron (2019) demonstrated that while spatial variability of soil properties is significant, it might not alone influence crop response to irrigation practices. Their study indicated that these soil properties did not exhibit a discernible spatial structure suitable for establishing specific management zones.

The creation of irrigation management zones typically involves the utilization of site-specific soil characteristics, including soil texture, soil organic matter, topography, infiltration rates, soil available water content, and yield zones (Franzen et al. 2002). This approach allows for the division of a field into distinct zones, each with relatively homogeneous attributes that influence irrigation requirements. Site-specific irrigation management (SSIM) is defined as a practice where irrigation timing or depth is tailored to the crop's water needs within designated sub-areas of a field (King et al. 2006). This approach seeks to optimize irrigation by delivering varying amounts of water precisely where and when they are required. Variable-rate irrigation is a key component of SSIM, involving the application of the appropriate water depth at the right location and time using suitable technology. This method enables the application of optimal water depths within each zone, ultimately leading to improved water productivity (de Lara et al. 2018). SSIM harnesses technology and intensive data to facilitate informed decision-making in water management, enhancing the implementation of these decisions for better agricultural outcomes (Krishna 2013). Successful SSIM implementation relies on access to information about soil and/or crop water status within each management zone. The delineation of site-specific irrigation management zones (SSIMZ) crucially relies on understanding soil hydraulic characteristics. These attributes define the optimal soil water parameters for each management zone, contributing to effective irrigation practices within varying areas of the field (Hedley and Yule 2009a).

One statistical method frequently employed for delineating management zones is fuzzy K-means clustering. This approach involves using fuzzy theory and clustering techniques to identify distinct regions within a field that share similar attributes. This method has been widely explored in the literature for both soil and irrigation management zone determination (Mc Bratney and de Gruijter 1992; Oliveria 2003; Davatgar et al. 2012;

Hedley 2015; Sanchis et al. 2019; Viáis Neto et al. 2019; Chen et al. 2020; Moharana et al. 2020; Shukla and Sharma 2023). This technique offers several advantages for creating IMZs that optimize irrigation practices. Firstly, fuzzy k-means effectively handles the inherent spatial variability of soil attributes. Secondly, fuzzy-k-means enables users to assign membership degrees to data points based on their subjective perspectives. Thirdly, this approach enhances the accuracy and precision of land resource assessment and classification (Kollias and Kalivas 1998). Reyes et al. (2019) effectively demonstrated the applicability of cluster analyses for delineating management zones within a farmer's field (an area of ~ 27 ha). By utilizing relatively easily accessible information, they showcased the potential of these methods for optimizing irrigation practices in a practical context.

Traditional rice irrigation systems, particularly those involving continuous flooding early in the growing season, have been associated with substantial water consumption (Goncalves et al. 2022; Carracelas et al. 2019; Yadav et al. 2017). However, in recent years, a combination of factors, such as drought, reduced rainfall, declining water resources, and competition for water between agricultural, industrial, and urban sectors, have highlighted inefficiencies in the management of continuous flood irrigation practices. This situation has prompted the need for a more efficient and sustainable approach to rice irrigation, particularly in regions facing water scarcity challenges.

Paddy fields in Guilan province are irrigated by uniform irrigation method. As a result, due to the difference in soil hydro-physical characteristics, a field that is irrigated uniformly with an application of water use would create water deficits in some areas within a field and surpluses in others (King et al. 2006). Consequently, it is necessary to divide a field into a few relatively uniform homogeneous zones as a practical, environmentally sustainable, and cost-effective approach for proper use of water resources. So, this study is based on the hypothesis that management zone delineation has great potential for solving the challenge of uniform irrigation method in studied paddy field. Therefore, the aim of this study was (i) to estimate the net and gross irrigation requirements variability using spatial variability of soil physical properties for rice and (ii) to assess the potential of the fuzzy k-means algorithm for management zone delineation and determine the number of homogeneous site-specific irrigation management zone in the paddy fields of Shaft-Fouman region (Guilan province, Iran).

2 Materials and Methods

2.1 Study Area

The study focuses on paddy fields located in the Shaft and Fouman counties of Guilan province in the northern part of

Iran. These paddy fields collectively cover an area of 280 square kilometers. The geographical coordinates of the study area fall within 36° 56' to 37° 18' N latitude and 48° 52' to 49° 10' E longitude, as depicted in Fig. 1. The climate in this region is characterized as moderately moist, bordering on sub-humid. The average annual temperature recorded in the area is approximately 16 °C, and the region experiences an average annual precipitation of around 1260 mm.

The study area is characterized by several distinct physiographic units, including coastal lowlands, alluvial plains, and a few old plateaus. The main land use in this region is rice paddy fields. The soil texture across these areas ranges from loam to clay, with a notable presence of high expansive smectite and moderate expansive vermiculite (Davatgar et al. 2005). The topography of the region is nearly flat, with slopes measuring less than 1%. The predominant soil group found in the study area is categorized as Aquept. Early spring sees land preparation conducted between seven to thirty days before the transplanting of rice seedlings. The Sepidrud dam water distribution network serves as the primary source of irrigation water for the paddy fields within the study area. Intermittent flooding is the irrigation method employed for these paddy fields. Electrical conductivity (EC) and sodium absorption ratio (SAR) of the irrigation water during the growing season were in the range of 1450 to 1745 $\mu\text{s}/\text{cm}$ and 0.8 to 8.10, respectively. According to the saline water classification by FAO (Rhoades 1992), the quality of irrigation water of soils was slightly saline, which was suitable for using in paddy fields. The irrigation water content, number of irrigation, and irrigation time were 9374 to 11104 m^3/ha , 16 times, and 5-day interval.

In the cultivation of rice, a key practice involves puddling the soil under saturated conditions. This process aims to create anaerobic conditions suitable for optimal rice growth. This practice serves several purposes: Puddling creates a plow layer in the soil profile, which effectively reduces the hydraulic conductivity of the soil. The altered soil structure resulting from puddling allows the soil to maintain a higher water content. Furthermore, puddling leads to the destruction of soil aggregates and macropores, and the soil becomes more homogeneous in its water-holding capacity and structure (Janssen and Lennartz 2007).

2.2 Soil Sampling and laboratory Analyses

A total of 120 soil samples were systematically collected from the top layer of soil (0–30 cm) within the paddy fields. The sampling points were strategically distributed across the entire study area, ensuring comprehensive coverage. However, it is worth noting that sampling was limited in the western and southern parts of the study area due to the presence of mountainous terrain in those regions. The distribution

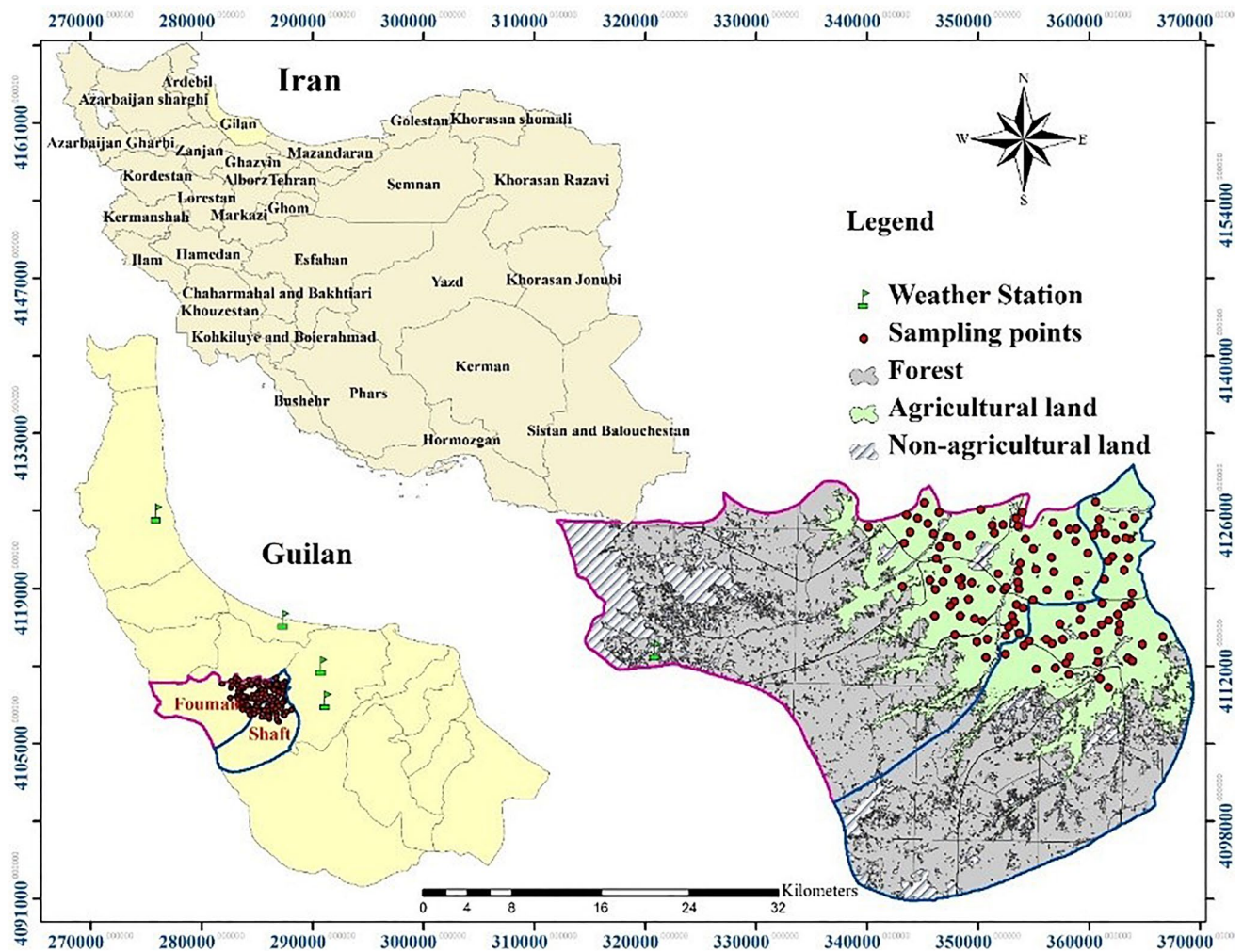


Fig. 1 Schematic view of the study area and locations of soil sampling points and weather stations

of both soil sampling points and weather stations has been visually depicted in Fig. 1.

The collected soil samples underwent a series of standardized laboratory analyses to determine various chemical and physical attributes. The methods employed for these analyses were as follows: soil texture using the hydrometer method, as described by Klute (1986), soil organic carbon (OC) was determined using the wet oxidation titrimetric method, as outlined in Page et al. (1982), dry (BD_{dry}) and wet bulk densities (BD_{wet}) of the soil were measured using the core method, the saturated water content (θ_s) of the soil samples was determined using the oven-drying method specified by Klute (1986), and hydraulic conductivity at saturated conditions (K_s) was measured using the falling head method, following the procedure outlined in Booltink and Buma (2002). A pressure plate apparatus, as described by Dan and Hopmans (2002), was utilized to measure soil water contents at

different tensions, including 33 kPa (field capacity, θ_{FC}), 80 kPa (θ_{80}), 130 kPa (θ_{130}), and 1500 kPa (permanent wilting point, θ_{PWP}). Furthermore, in accordance with the findings reported by Davatgar et al. (2009), the thresholds of θ_{80} and θ_{130} were significant in terms of rice growth and yield. They observed that beyond θ_{80} , rice leaf relative growth, and transpiration begin to decline, and θ_{130} marks the point at which rice yield decreases by 50%. For the calculation of soil available water (SAW) and soil readily available water (SRAW), the methodology outlined by Ceddia et al. (2014) was followed as below:

$$SAW = \theta_s - \theta_{PWP} \quad (1)$$

$$SRAW = \theta_s - \theta_{80kPa} \quad (2)$$

Shrinkage index (SI) that describes the shrinkage-swelling potential of the soils was calculated using Eq. (3) (Reeve et al. 1980):

$$SI = \frac{1}{BD_{dry}} - \frac{1}{BD_{wet}} \quad (3)$$

where BD_{wet} and BD_{dry} are bulk density of soil at zero water tension and oven dry conditions, respectively.

2.3 Yield Measurement

Rice yield assessment was conducted during the ripening stage, specifically in mid-August. The measurement process involved the establishment of plots with an area of 1 square meter (1×1 m) at the various sampling locations within the study area.

2.4 Estimating Reference Potential Evapotranspiration

The study utilized meteorological data spanning from 2009 to 2018, collected from four closely located weather stations in the vicinity of the study area including Rasht airport, Rasht Agricultural Meteorology, Anzali, and Talesh (Fig. 1) to calculate the reference potential evapotranspiration (ET_0). Several meteorological parameters including the altitude of the weather stations, the minimum and maximum temperatures (in degrees Celsius), relative humidity, sunshine hours, and wind speed (in kilometers per day) were employed to calculate the reference potential evapotranspiration (ET_0) using the FAO-56 Penman-Monteith (FAOPM) method. This method expressed through the following mathematical equation, as outlined in Allen et al. (1998), is considered as a standard and the most precise method to estimate ET_0 in the study area:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \left[\frac{890}{T + 273} \right] U_2 (e_a - e_d)}{\Delta + \gamma(1 + 0.34U_2)} \quad (4)$$

where ET_0 is the reference potential evapotranspiration (mm/day); R_n is the net radiation at the reference surface (MJ/m^2d); G is soil heat flux (MJ/m^2d); T is the average air temperature ($^{\circ}C$); U_2 is the wind speed measured at 2 m height (m/s); $(e_a - e_d)$ is the vapor pressure deficit (kPa); Δ is the slope of the vapor pressure curve ($kPa/^{\circ}C$); γ is the psychrometric constant ($kPa/^{\circ}C$).

2.5 Estimating Standard Crop Evapotranspiration

Standard crop evapotranspiration (ET_c) was estimated based on ET_0 and crop coefficient (K_c) as below (Allen et al. 1998):

$$ET_c = ET_0 \cdot K_c \quad (5)$$

To estimate the standard crop evapotranspiration (ET_c), crop coefficients (K_c) corresponding to different phenological stages of the rice plant were applied. The study utilized

crop coefficients determined through a water balance approach within rice fields, as proposed by Yazdani (2017) and Modabberi et al. (2014). The specific crop coefficients applied in this study for different phenological stages of rice were as follows:

- (i) Initial stage: $K_c = 1.0$
- (ii) Vegetative stage: $K_c = 1.0$ to 1.3
- (iii) Reproductive stage: $K_c = 1.3$
- (iv) Ripening stage: $K_c = 0.85$ to 1.0

2.6 Estimating Effective Rainfall

Effective rainfall, often denoted as P_{eff} , represents the portion of total rainfall that is actually available for crop use after accounting for losses due to deep percolation and surface runoff. Determining P_{eff} is important for estimating the net irrigation requirement (Clarke et al. 2000) which helps farmers and water resource managers make informed decisions about irrigation scheduling and water management. The method proposed by the US Department of Agriculture (USDA) and Soil Conservation Service (SCS) commonly used to calculate P_{eff} is as follows (Jensen et al. 1990):

$$P_{eff} = \frac{P_{total}}{125} \times (125 - 0.2P_{total}) \text{ for } P_{total} \leq 250 \quad (6)$$

$$P_{eff} = (125 + 0.1 \times P_{total}) \text{ for } P_{total} > 250 \text{ mm} \quad (7)$$

where P_{total} is the total rainfall (mm) in the monthly time interval.

2.7 Determining Net Irrigation Water Requirement (NIWR)

The term “Net Irrigation Water Requirement” (NIWR) refers to the depth or amount of irrigation water needed for crop growth or to raise the soil moisture level to field capacity (FC). The NIWR per unit of irrigated area during the growing season is typically computed as follows:

$$NIWR = ET_c - P_{eff} \quad (8)$$

2.8 Determining Gross Irrigation Water Requirement (GIWR)

The term gross irrigation water requirement (GIWR) represents the depth of water that must be supplied through irrigation to meet the crop’s evapotranspiration (ET_c) and leaching requirements and does not include water from stored soil moisture or natural precipitation (Jensen et al. 1990). The calculation of GIWR typically involves several components, with the main component being the estimation of ET_c . The

FAO-56 (Food and Agriculture Organization) guidelines, as outlined in the manual by Allen et al. (1998), are widely used worldwide to determine GIWR. To determine GIWR, the water needed for land preparation and water losses due to deep percolation and horizontal seepage were considered.

Puddling is a common practice in lowland rice fields to create a hard pan and reduce deep percolation water loss. It was reported that a significant portion of water, up to a third of the total water needed for rice growing, is consumed for wet land preparation (<http://www.knowledgebank.irri/>). Vertical losses and seepage depend on soil type.

Deep percolation was determined based on the saturated hydraulic conductivity (K_s) of the soil in 120 sampling locations used in this study. The study chose to neglect the portion of water losses through horizontal seepage. This is because water lost through horizontal seepage tends to enter neighboring farms and can be consumed by the crop. The GIWR for the paddy fields was calculated by taking one-third (1/3) of the total water needed for rice growing (NIWR) and soil hydraulic conductivity (K_s) as follows:

$$GIWR = NIWR + 0.33NIWR + K_s \quad (9)$$

2.9 Specific Analysis for Determining Irrigation Management Zones (IMZs)

The study area was divided into different unique IMZs using the fuzzy k-means clustering approach. The primary objective of fuzzy k-means clustering is to create homogeneous groups or clusters by minimizing within-group variability and maximizing among-group variability. Unlike traditional clustering, where a data point exclusively belongs to a single cluster, fuzzy clustering accommodates the idea that a data point can have varying degrees of membership in multiple clusters while reducing the impact of outliers on the clustering results (Brown 1998). Fuzzy k-means aims to minimize the functional within-class sum square errors (Hezarjaribi 2008).

In this study, fuzzy-k-means, as an unsupervised continuous classification approach, was applied to divide the field into 2 to 6 clusters using the FuzME program (Minasny and Mc Bratney 2006). Settings used in the FuzME software were as follows (Minasny and Mc Bratney 2006): input variables including clay, OC, SI, K_s , SAW, SRAW, and GIWR, the maximum number of iterations as 300, the stopping criterion of 0.0001, the minimum and maximum number of zones as 2 and 6, respectively, and the fuzziness exponent as 1.5 according to Fridgen et al. (2004) and Reyniers et al. (2006).

The influence of varying the number of classes was examined using two validity functions of Modified Partition Entropy (MPE) and fuzzy performance index (FPI). MPE

shows the degree of disorganization created by a specified number of classes, while FPI shows the degree of fuzziness generated by a specified number of classes (Minasny and McBratney 2006). Both MPE and FPI are limited between 0 and 1.0. As FPI values approach 1, the degree of membership sharing among clusters increases. In contrast, classes become more distinct with less membership sharing when FPI values approach decrease towards 0. A higher MPE value indicates more disorganization or randomness, while a lower value indicates better organization or structure in the data. Therefore, by minimizing the MPE and FPI validity functions, the optimum number of classes (structured and continuous) can be established (Mc Bratney and Moore 1985; Boydell and Mc Bratney 1999).

2.10 Geostatistical Analysis

Before applying geostatistical methods, the normality of the data and the existence of probable trends and outliers were checked (Robinson and Metternicht 2006). Square root or natural log transformations were used when the data significantly deviated from normal distribution. The GS⁺ (5.1) software packages were used to perform geostatistical analyses and to evaluate the spatial structure of the soil properties. Experimental semivariogram of the studied soil attributes was calculated, and the common theoretical models including exponential, Gaussian, and spherical were fitted. The most suitable and representative models were determined based on their ability to model the spatial structure (the nugget to sill ratio), goodness of fit (determination coefficient, R^2), and their error (residual sum of square, RSS) following Moosavi and Sepaskhah (2012). Furthermore, the anisotropic behavior of spatial structure for each soil attribute was evaluated based on the calculated directional and the surface variograms. If there was little difference between directional semivariograms or if surface semivariograms appeared symmetric and circular, it suggested isotropic behavior, and the isotropic semivariogram model was applied in the kriging prediction approach.

2.11 Statistical Analysis

Descriptive statistics of the studied attributes like minimum, maximum, mean, median, standard deviation, coefficient of variation (CV), skewness, and kurtosis were calculated using SPSS 16.0 software packages (SPSS Inc., Chicago IL). Furthermore, the Pearson correlation that is known as the best method measuring association between the variables of interest and a measure of statistical relationship between two variables was examined between the studied soil attributes. Furthermore, the normality of the data was checked using the Kolmogorov-Smirnov test ($p < 0.05$).

Both inverse distance weighting (IDW) and kriging approaches (ordinary kriging) were applied to predict the studied soil attributes, and the selection of the most suitable prediction method was based on cross validation. Finally, maps were prepared using the predicted values of the suitable approach determined. All of these geostatistical analyses and map preparations were performed using ArcGIS (10.4) software packages.

To determine the accuracy of the produced maps, a statistical comparison of the results was carried out in terms of mean error (ME) and normalized root mean square error (NRMSE).

3 Results

3.1 Exploratory Data Analysis

Descriptive statistics of the soil chemical and physical properties studied are shown in Table 1. Approximately 75% of the studied soils fall into the fine textured class (Fig. 2). Furthermore, expansive montmorillonite with high swelling and shrinkage potential is the dominant clay mineral in the study area (Davatgar et al. 2005). The shrinkage index in the study area falls within the range of 26.38 to 62.48, placing the soils in the medium to very high shrinkage class, as per the classification proposed by Ranganatham and Satyanarayana (1965). Therefore, it can lead to the formation of cracks during water stress, which can result in water loss and damage to plant roots.

Based on the Kolmogorov-Smirnov test, the studied soil properties were normally distributed (except for K_s and OC that show significant deviation from normal distribution). The closeness of the mean and the median values is another criterion indicating a normal distribution of the attributes (Godwin and Miller 2003).

Coefficient of variation (CV), as a measure of the normalized variability with respect to the mean value, changed from 12 (for the SAW) to 50% (for K_s value). SAW values showed low variability (CV < 15%), whereas, OC, clay, SI, and SRAW had moderate (16 < CV < 35%) and K_s had high variability (CV > 35%) (Wilding and Dress 1983). The results also showed that K_s had the largest skewness, kurtosis coefficients, and non-normal frequency distribution (Table 1). Variables related to mass transfer, such as K_s , which is an indicator of the soil infiltration, often show a wide range of values as a result of the presence of small and large pores in the soil (Worrick and Vanes 2002).

3.2 Correlation Among Soil Properties

The Pearson correlation coefficient (r) between the soil attributes in the study area is shown in Table 2. There was

Table 1 Summary statistics of the studied soil chemical and physical properties

Soil variables/indices	Minimum	Maximum	Mean	Median	Standard deviation	Skewness	Kurtosis	Coefficient of variation (CV)	Variability classes ^a	Kolmogorov-Smirnov statistics
OC (%)	1.16	4.26	2.40	2.25	0.69	0.62	-0.38	28.75	Moderate	1.39*
Clay (%)	12.00	56.00	38.51	40.00	9.46	-0.35	-0.38	24.56	Moderate	0.96
K_s (cm/day)	0.05	0.51	0.21	0.17	0.10	1.21	1.02	50.35	High	1.48*
SI (%)	26.38	62.84	43.90	44.20	6.97	-0.17	-0.13	15.87	Moderate	0.53
SAW (%)	24.18	49.82	38.26	38.56	4.76	-0.17	0.25	12.43	Low	0.76
SRAW (%)	9.47	36.57	22.45	22.17	4.93	0.15	0.22	21.96	Moderate	0.70

OC, organic carbon; K_s , saturated hydraulic conductivity; SI, shrinkage index; SAW, soil available water; SRAW, soil readily available water

*Significant at $p < 0.05$

^aVariability classes adopted by Wilding and Dress (1983). Low variability (CV < 15%), moderate variability (16 < CV < 35%), and high variability (CV > 35%)

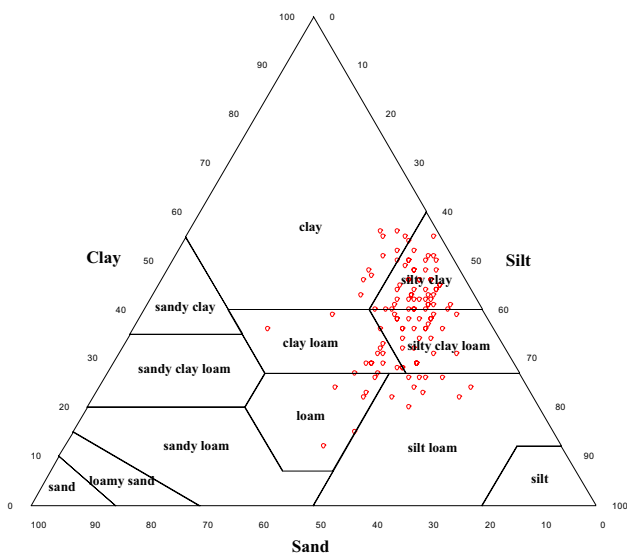


Fig. 2 Texture class distribution of the studied soils based on the texture triangle proposed by USDA

a significant correlation between clay and K_s ($r = -0.42$, $p < 0.01$), SI ($r = 0.40$, $p < 0.01$), and SRAW ($r = 0.48$, $p < 0.01$). SI had significant correlations ($p < 0.01$) with OC ($r = 0.51$), SAW ($r = 0.45$), and SRAW ($r = 0.66$). SAW and SRAW had significant correlations with SI. The highest correlation was obtained between SAW and SRAW ($r = 0.81$, $p < 0.01$). Yield had a significant correlation with clay and K_s . Considering the high variability of K_s (Table 1) and its correlation with yield (Table 2), it seems necessary to use K_s as a site-specific value for determining GIWR.

3.3 Spatial Variability Analysis

Results of the Kolmogorov-Smirnov test showed that OC and K_s followed non-normal distribution. Furthermore, the closeness of the mean and median values confirms the normal distribution of the data. Values of OC, K_s , and SRAW

were positively skewed. The K_s also had the highest skewness and kurtosis coefficients (Table 1). Therefore, the values were log transformed before geostatistical analysis.

Table 3 shows the parameter of semivariogram for the studied soil attributes. In the present study, soil attributes showed a spatial structure with dominant spherical models, whereas semivariogram of SAW followed an exponential model (Table 3).

The nugget (C_0) to sill (C_0+C) ratio (the random to the total variance ratio) was used to evaluate the spatial dependency (structure) of the data. Regarding the $C_0/(C_0+C)$ ratio, if the ratio is less than 25%, 25% to 75%, and greater than 75%, the attributes belonged to the classes of strong, moderate, and weak spatial correlation, respectively. Spatial distribution of the studied soil properties is shown in Fig. 3.

3.4 Irrigation Water Requirement

3.4.1 Net Irrigation Water Requirement

Meteorological parameters along with ET_0 , ET_c , P_{eff} , and NIWR are listed in Table 4. The highest ET_0 (528 mm) recorded among the studied stations was observed at the Anzali station (Table 4). Higher sunshine and wind speed may be the reasons for higher ET_0 observed at the Anzali station during the growing season. The differences in ET_0 values among the studied stations indicate variations in climatological parameters in the study region.

3.4.2 Gross Irrigation Water Requirement

The values of NIWR were interpolated for 120 sampling points in the study area using the inverse distance weighting (IDW) method and the data of four meteorological stations (Rasht airport, Rasht agricultural weather station, Anzali, and Talesh). The average estimated value for NIWR was 503 mm. Based on those proposed by the International Rice Research Institute (IRRI) (<http://www.knowledgebank.irri/>), one third of this depth (i.e., 168 mm) was considered as

Table 2 The Pearson correlation coefficients (r) between the studied soil attributes and rice yield

Soil variables	OC	Clay	K_s	SI	SAW	SRAW
OC (%)	1					
Clay (%)	0.01	1				
K_s (cm/day)	0.1	0.42**	1			
SI (%)	0.51**	0.40**	0.01	1		
SAW (%)	0.12	0.11	-0.03	0.45**	1	
SRAW (%)	0.17	0.48**	-0.16	0.66**	0.81**	1
Yield (kg/ha)	0.18	0.33**	-0.34**	0.27	-0.04	0.17

OC, organic carbon; K_s , saturated hydraulic conductivity; SI, shrinkage index; SAW, soil available water; SRAW, soil readily available water

**Significant at $p < 0.01$

Table 3 The best fitted model to the semivariogram of soil physical/chemical attributes and their parameters along with the modeling statistical measures

Variables	Model	Method	Nugget (C0)	Sill (C0 + C)	Range, A (m)	Nugget to sill ratio, C0/(C0+C) (%)	R ²	RSS	Spatial structure classes ^a
OC (%)	Spherical	OK	0.009	0.044	2000	20	0.72	8.5 × 10 ⁻⁵	Strong
Clay (%)	Spherical	OK	42	116	18000	36	0.95	352	Moderate
K _s (cm/day)	Spherical	OK	0.085	0.29	2000	29	0.72	7.11 × 10 ⁻³	Moderate
SI (%)	Spherical	OK	28	47	3600	60	0.68	63.8	Moderate
SAW (%)	Exponential	OK	6.20	9.60	4200	65	0.72	1.98	Moderate
SRAW (%)	Spherical	OK	0.11	0.26	2000	42	0.68	1.93 × 10 ⁻³	Moderate

OC, organic carbon; K_s, saturated hydraulic conductivity; SI, shrinkage index; SAW, soil available water; SRAW, soil readily available water; OK, ordinary kriging; R², determination coefficient; RSS, residual sum of square

^aSpatial structure classes adopted by Cambardella et al. (1994): The nugget to sill ratios of <25%, 25 to 75%, and >75% indicate strong, moderate, and weak spatial structure classes, respectively

the depth of water required for land preparation and puddling. Because K_s was non-uniform based on the coefficient of variation statistics, to calculate GIWR in each sampling point, the value of K_s was added to the NIWR and the portion of water required for land preparation and puddling (Eq. (9)). In this study, the amount of horizontal seepage was not considered. Talebpour (2019) reported a horizontal seepage value of 14.3 mm during the entire growing season in Guilan paddy soils at the farm scale. Bouman et al. (2007) stated that though seepage losses at the field scale, it is often captured and reused downstream and does not necessarily lead to true water depletion at the irrigation area or basin scales.

Spatial analysis revealed that the GIWR variable followed the spherical semivariogram model with a weak spatial structure (nugget to sill ratio greater than 75%) (results not shown). Therefore, for its spatial distribution, the inverse distance weighting (IDW) method was used (Fig. 4).

3.5 Determining the Optimum Number of Management Zones

The values of MPE and FPI validity functions were plotted versus the number of management zones (Fig. 5). In the present study, there were two distinct options, FPI with four clusters and MPE with five clusters. Xin-Zhang (2009) stated that a maximum of four management zones can be considered for practical uses. Therefore, four clusters (management zones) were identified in this study. Using similar selection criteria, other researchers have also reported management zones for their study (Davatgar et al. 2012; Chen et al. 2020).

The resultant map of irrigation management zones representing four management zones is shown in Fig. 6. There were significant differences among some characteristics (clay, K_s, yield and GIWR) in the four determined irrigation management zones; while soil readily available water, soil

available water, shrinkage index, and organic carbon were not significantly different (Table 5).

4 Discussion

Soil physical and chemical properties had strong and moderate spatial correlation. The mentioned spatial correlations are related to intrinsic factors (soil forming process), combination of intrinsic and extrinsic factors (soil management process), and extrinsic factors (Cambardella et al. 1994). The nugget to sill ratio only for OC was less than 25%, indicating that OC belongs to the strong spatial dependency class. SRAW, SAW, SI, K_s, and clay content had a moderate spatial structure which could have resulted from a combination of intrinsic factors (parent material, soil texture, and mineral type) and management factors (soil puddling and flooded irrigation management) (Metwally et al. 2019; Rahul et al. 2019; Zeraatpisheh et al. 2020). The range of semivariogram representing the maximum distance at which spatial autocorrelation occurs was the highest (18000 m) for clay content. Lopez-Granados et al. (2002) suggest that the wide range of a variable is affected by anthropogenic activities. In paddy soils, especially during the puddling process, soil and water are intentionally mixed together to create a more homogeneous area with strong spatial autocorrelation. All studied variables followed sill-bounded semivariogram models. Therefore, the ordinary kriging method was used for predicting the variables at unsampled locations and zoning the study area.

The maps of soil properties showed that the values of OC were less in the western half as well as in the north and southeast parts of the study area. Water holding capacity of soil decreased due to reduced organic carbon. There are spatial similarities between the soil organic carbon and SRAW. SRAW is the value of soil water content retained between the 0 and 80 kPa suction. In paddy fields, the farmers try to

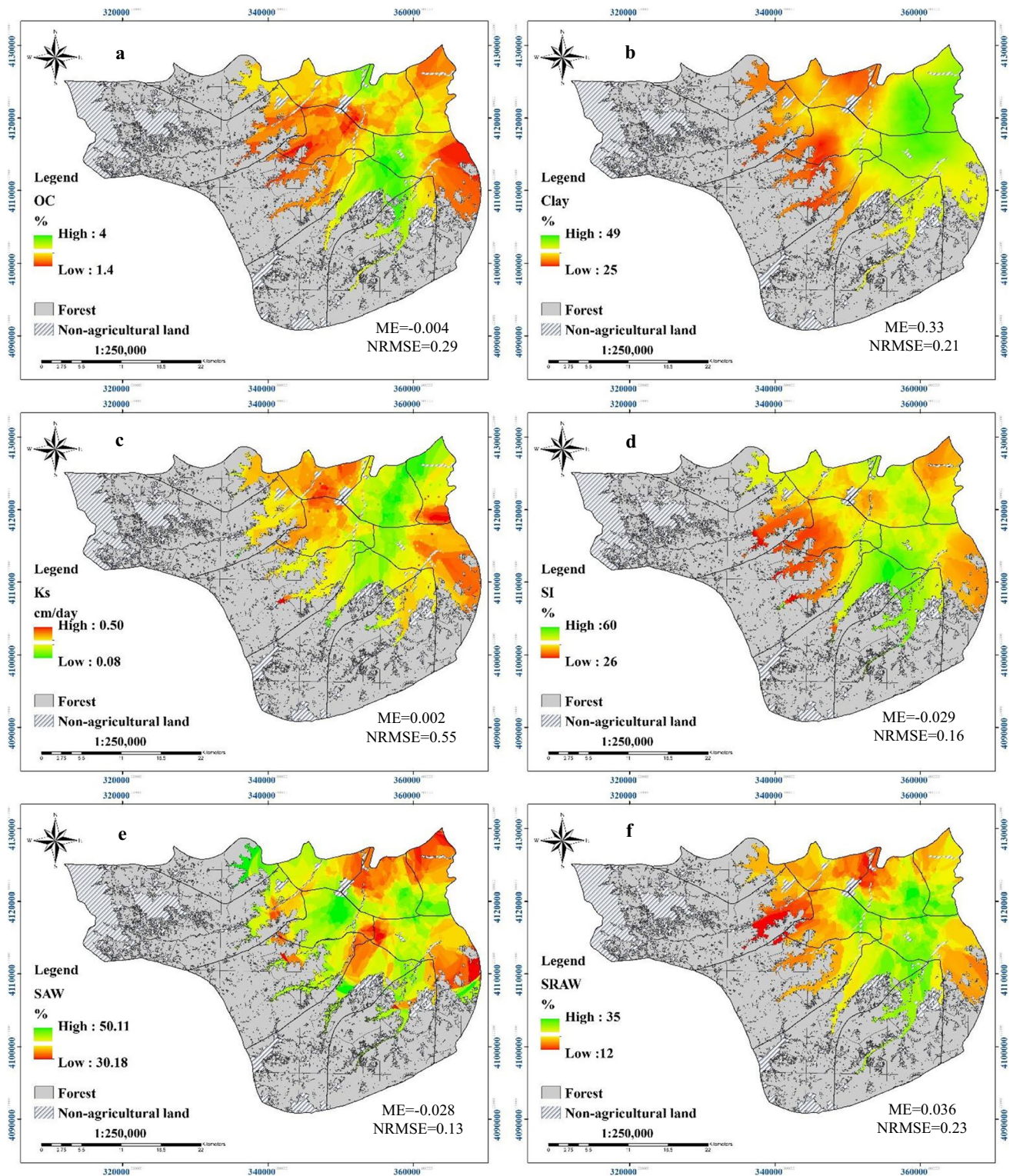


Fig. 3 Maps of the kriged values for organic carbon, OC (a); clay content (b); saturated hydraulic conductivity, K_s (c); shrinkage index, SI (d); soil available water content, SAW (e); and soil readily available water, SRAW (f), in the studied paddy fields

Table 4 The mean values of climatological parameters at four weather stations during rice growth season from May 5 to August 6 (94 days) from 2009 to 2018

Weather station	Longitude	Latitude	Rainfall (mm)	Mean temperature (°C)	Humidity (%)	Sunshine (h)	Wind speed (km/day)	ET ₀ (mm)	ET _c (mm)	P _{eff} (mm)	NIWR (mm)
Rasht airport	49.62	37.32	90.05	27.08	76.15	7.48	1.64	477	568	83	492
Rasht agricultural weather station	49.65	37.20	73.50	26.93	76.38	7.75	1.50	482	569	67	509
Anzali	49.46	37.48	115.15	26.50	76.93	8.69	3.07	528	624	101	521
Talesh	48.90	37.84	126.10	25.84	72.04	6.79	1.99	461	546	114	433

ET₀, reference evapotranspiration; ET_c, actual evapotranspiration; P_{eff}, effective rain; NIWR, net irrigation water requirement

keep the soil water content close to saturation conditions during the growing season. The results were in agreement with those obtained by Minasny and Mc Bratney (2018). They stated that organic carbon has the greatest effect on saturated soil water content among the other studied soil water properties including field capacity and wilting point.

Clay content has an important role in rice cultivation. In other words, most of the soil physical, chemical, and hydrological properties are mainly controlled by clay content and soil type. For instance, water retention by soil, water transportation within soil, and the stability of aggregates are remarkably influenced by clay content. The soils with high clay content are suitable for rice production due to their high capacity for storing nutrients through exchange sites, as well as because more pores have a large capacity for storing (retention) water (De Datta 1981; Dengiz 2013). In the eastern half of the studied region, the clay content was low. As a result, the SRAW was also low. On the other hand, small pores of soil reduce the K_s , leading to higher water content in the soil. Spatial distribution maps showed that in areas with high clay content, K_s was low. Such variability in saturated hydraulic conductivity could considerably influence the leaching of water and fertilizers under the root zone following irrigation events (Létourneau and Caron 2019).

Spatial distribution of soil shrinkage index (SI) showed that there is a wide range of medium to high capacity for shrinkage in the studied paddy fields. The SI in the west, northeast, and southeast parts of the region was less than that of the other parts. Although the linear correlation between OC and SI was not statistically significant, the spatial distribution of these two variables was relatively similar. On the other hand, in the central parts of the study region, where the clay content was high, the value of SI was also high. SI had a significant ($p < 0.05$) positive correlation ($r = 0.40$) with clay content.

The average NIWR in the four stations ranged from 433 to 521 mm. The results were similar to those of Asadi-Oskouei (2017) who reported rice evapotranspiration as 463 mm in the Lysimeter station of the Rice Research Institute of Iran (RRII), 20 km from the studied area during the rice growing season. Surendran et al. (2014) showed that differences in irrigation requirements might be due to the changes in temperature, sunshine hours, wind speed, and a decrease in effective rainfall.

Based on GIWR, the greatest distinction of management zones was IMZ1: 709 to 796 mm/94 days; IMZ2: 797 to 869 mm/94 days; IMZ3: 870 to 961 mm/94 days; and IMZ4: 962 to 1082 mm/94days. In IMZ4, where GIWR was the highest, the clay content and K_s were the lowest and highest among the other zones, respectively. Water productivity is expected to be lower, and production risk is expected to be higher in the occurrence of water deficit conditions. GIWR was the lowest in IMZ1. In this zone, the clay content and yield were higher, and K_s was lower than that of the other

Fig. 4 Spatial distribution of gross irrigation water requirement (GIWR) interpolated using the inverse distance weighting (IDW) method in the study area

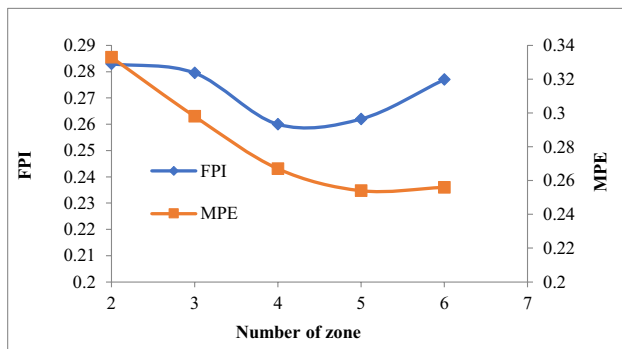
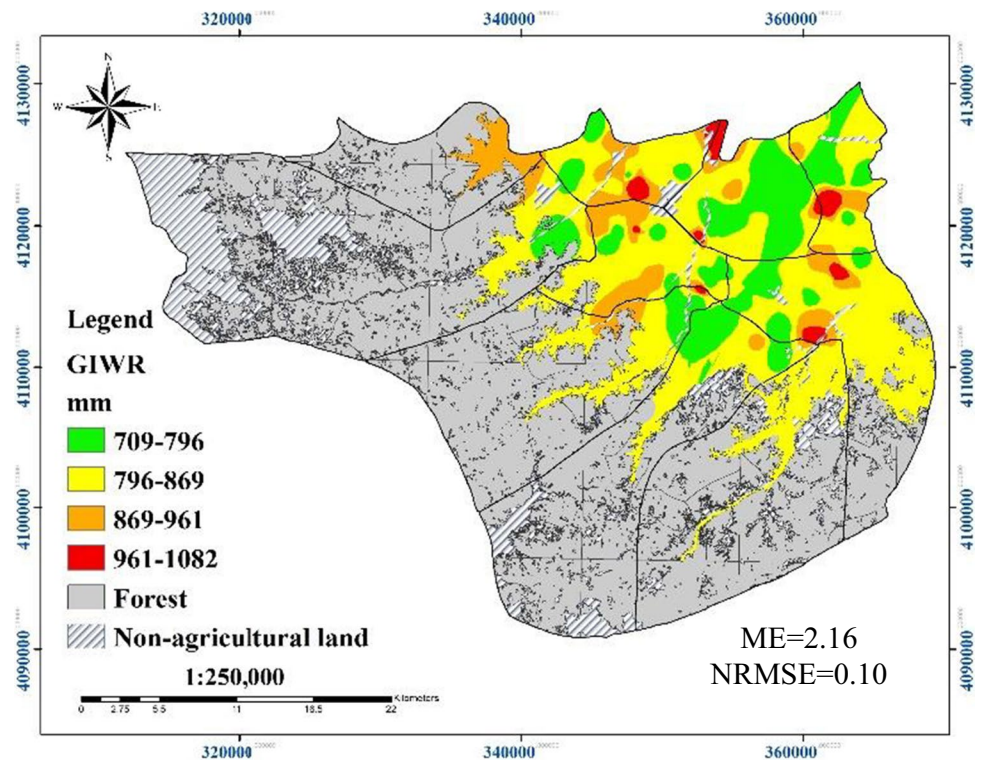


Fig. 5 Plots of the modified partition entropy (MPE) and fuzzy performance index (FPI) versus the number of clusters

zones. IMZ4 and IMZ1 were the smallest and the largest irrigation zones, which included 4.28% and 40.2% of the whole study area, respectively. The results showed irrigation management zones that address the natural spatial variation of soil properties, decreased irrigation requirements in comparison with the uniform irrigation (9374 to 11104 m³/ha) in the studied field. Moharana et al. (2022) presented a method for delineation of irrigation management zones (IMZ) with soil hydro-physical properties. They stated that IMZ-based precision irrigation can be useful in the effective use of water resources in different stages of crop growth and improving overall productivity. Flint et al. (2023) delineated five management zones from historic yield and ET

using k-means clustering algorithm in winter wheat. Their results showed that management zones effectively reduced irrigation requirements in the studied field. Other researchers reported that management zones can increase water use efficiency and delay the onset of crop water stress leading to higher yield and water savings (O’Shaughnessy et al. 2019; Lo et al. 2017; Hedley and Yule 2009b).

Paddy soils with high clay content retain higher amounts of water. High clay content and type of clay minerals (montmorillonite) in the study area result in a large specific surface area and higher water holding capacity. On the other hand, as clay content increases, K_s decreases due to the increase in the number of fine pores. Evans and Sadler (2013) stated that heavier soils (clay) have greater water-holding capacity due to smaller pores and do not drain quickly. As a result, by increasing clay content and reducing K_s , it is expected that zone 1 with a lower water requirement can contribute to higher rice yield if the soil in zone 1 contains sufficient nutrients for rice cultivation. Chen et al. (2020) noted similar observations and reported increases in yield under variable irrigation management. Similar contiguous management zones were recognized based on several soil properties by Yao et al. (2014), Moharana et al. (2022), Maleki et al. (2023), Flint et al. (2023), and Shukla and Sharma (2023). There was a significant correlation between yield, clay content, and K_s . The maximum similarity was obtained between the spatial distribution of rice yield and that of IMZ1 particularly in the central and northeastern parts of the region.

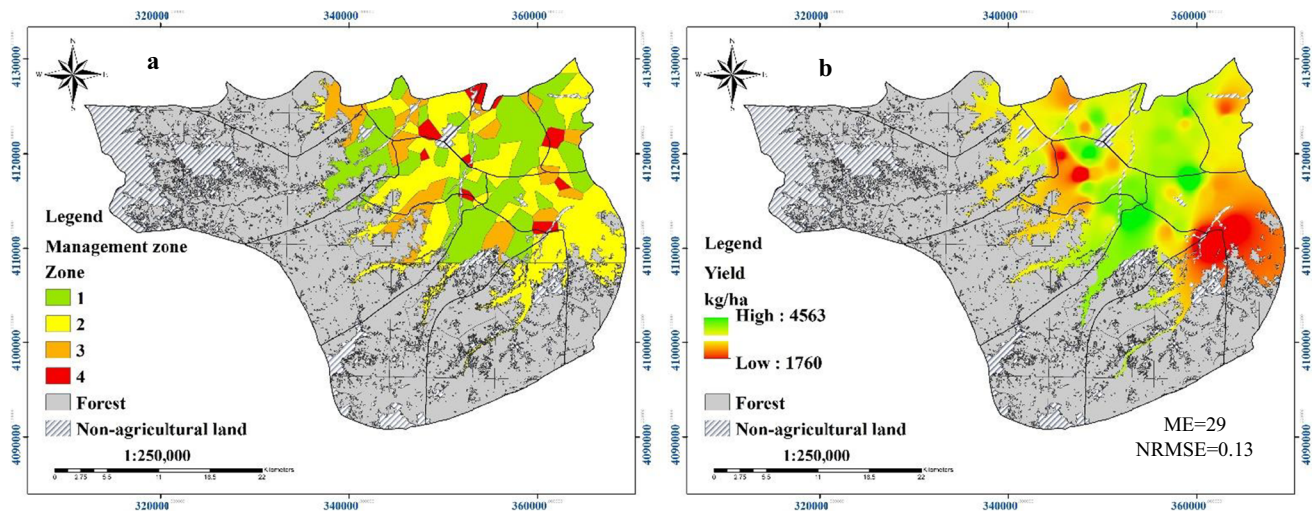


Fig. 6 The maps of management zones (a) and spatial distribution of rice yield (b) in the study area

Table 5 Mean values of soil attributes in the four prescribed management zones

MZ	Number of samples	Area (%)	Yield (kg/ha)	OC (%)	Clay (%)	SI (%)	K_s (cm/day)	SAW (%)	SRAW (%)	GIWR (mm/94 days)	Water productivity (kg/m ³)
1	43	40.20	3643 ^a	2.06 ^a	44 ^a	44.52 ^a	0.127 ^d	38.59 ^a	22.44 ^a	773 ^d	0.48 ^a
2	38	39.21	3419 ^{ab}	2.38 ^a	39 ^{ab}	45.27 ^a	0.192 ^c	39.96 ^a	23.46 ^a	825 ^c	0.41 ^b
3	16	16.31	3004 ^{bc}	2.39 ^a	34 ^b	41.93 ^a	0.310 ^b	38.02 ^a	20.88 ^a	920 ^b	0.33 ^c
4	9	4.28	2963 ^c	2.60 ^a	32 ^b	43.59 ^a	0.425 ^a	38.46 ^a	20.74 ^a	1012 ^a	0.27 ^c

Similar lowercase letters for each attribute indicate there is no significant difference among different management zones

MZ, management zone; OC, organic carbon; SI, shrinkage index; K_s , saturated hydraulic conductivity; SAW, soil available water; SRAW, soil readily available water; GIWR, gross irrigation water requirement

5 Conclusion

Irrigation management of paddy fields in the whole study area is done by intermittent flooding. The lack of consideration for variations in the gross irrigation, soil properties, and hydraulic characteristics can lead to both over-irrigation and under-irrigation in comparison with optimum irrigation water requirement in different areas within the same agricultural system. Site-specific irrigation management with dividing a field into four uniform homogeneous zones can be used for managing water resources and increasing its productivity in paddy fields. The results showed that soil hydro-physical properties due to non-uniformity and spatial variability have key roles to identify irrigation management zones. Results from fuzzy clustering indicated that the optimal number of irrigation management zones was four based on statistical analysis and one-way ANOVA analysis, which were different in terms of soil hydro-physical properties which affect water storage and

transmission and irrigation requirement. The proposed irrigation management approach aligns with sustainable agriculture practices and can have several benefits for rice production and water resource management.

Acknowledgements The authors acknowledge the financial support from the Shiraz University. Dr. Ali Reza Sepaskhah appreciates the financial support of Drought Research Center, On Farm Irrigation Water Management Center of Excellence, and Iran National Science Foundation (INSF). The authors also would like to thank the Soil and Water Department of Rice Research Institute of Iran (RRII) for providing the needed facilities. The first author wishes to thank S. Ahmadzadeh for assistance during the laboratory analyses.

Funding The research was funded by Shiraz University. Furthermore, all of the needed facilities were provided by Soil and Water Department of Rice Research Institute of Iran (RRII).

Data Availability Data will be available based on reasonable request.

Declarations

Competing Interests The authors declare no competing interests.

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