A NOVEL WATER INDEX (SWI) FOR SALTY WATER FROM LANDSAT 8 OLI/TIRS

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ABSTRACT:

Monitoring natural resources is one of the most important tasks in earth observation and remote sensing satellites. Water resources play a crucial role in the life of human on the planet. Among the water resources, salty lakes are of particular importance in biological, physical and environmental issues. In this study, a new Salty Water Index (SWI) for Landsat 8 Operational Land Imager (OLI) images is proposed based on salty lakes by particle swarm optimization (PSO), where water doesn't combine by cloud, shadow, and salty areas. SWI is implemented on four famous and important salty lakes with the proper distribution of the whole world and different Salinity, including Lake Assal, Great Salt Lake, Eyre Lake, and Lake Urmia. The performance of SWI is compared with other water indices by overall accuracy, f-score, kappa coefficient, and standard deviation to mean ratio. Results show the efficiency of SWI on all cases due to 0.0055 Standard deviation to mean for SWI compared to 0.0395, 0.0255, 0.0873, 0.0214, 0.0524, 0.0408 and 0.0375 for NDWI, MNDWI, AWEIsh, AWEI, WRI, MOWI, and MBWI, respectively. Also, Effectiveness criteria (E) determines the efficiency of each band of Landsat 8. In this regard, results show the high performance of Green and Near IR band in all conditions and relatively proper performance of some other bands based on a special condition of each case study. The proposed method is also suggested to readers to obtain novel spectral indices of other classes and other sensors.

1. INTRODUCTION

Water, the largest and one of the most significant and vital parts of the earth, plays an important role in the ecosystem, plant varieties, animal species, and the economy of the people (Sheng et al. 2016). Salty lakes have ecological values with natural properties that are affected by climatic and atmospheric changes and human activities (Sheng et al. 2016; Williams 2002). Environmental changes of Lake heavily influenced issues such as ecosystems, weather, plant varieties, animal varieties and also the life of people due to salt storm or drought. Therefore, timely monitoring and access to data of salty lakes are essential for policy making, decision making processes, and continuous water resource management.

Remote sensing satellites can provide a practical approach to map lakes systematically due to the low-cost, reliable information, wide coverage, repeatable observations, multi-band imagery and even real-time or near real time observations at both local and global scales (Sheng et al. 2016; Wang et al. 2018). Landsat 8 Operational Land Imager (OLI) has currently attracted more attention due to high-quality images. Therefore, Landsat-8 data, as the newest generation of Landsat series of satellites, are interesting to many researchers and many applications, especially water extraction.

There are many indices used for water detection. McFeeters (1996) proposed the normalized-difference water index (NDWI) to maximize reflectance of water in green band of MSS images while minimizing the low reflectance of near-infrared (NIR) band by water features. Nevertheless, extracted water maybe mixed with built-up land noise. Therefore, Xu (2006) proposed Modified Normalized Difference Water Index (MNDWI) by replacing NIR in NDWI with short-wave infrared (SWIR) band of TM images. Because water pixels may not be distinguished from dark surfaces, particularly shadows by two-band water indices, Feyisa et al. (2014) developed the new multi-band index, called Automated Water Extraction Index (AWEI), using five spectral bands of Landsat 5 TM. AWEIsh and AWEInsh were proposed to improve water extraction accuracy in areas with dark surfaces and areas with highly reflective surfaces. AWEI classifies edge pixels more accurately in comparison to MNDWI method. Water Ratio Index (WRI) was developed using adaboost algorithm from Landsat ETM+ imagery that eliminates the influence of built-up land, accumulated snow, and mountain shadow in comparison to NDWI (Shen and Li 2010).

Index	Equation
NDWI	$(\rho_{green} - \rho_{NIR})/(\rho_{green} + \rho_{NIR})$
MNDWI	$(\rho_{green} - \rho_{SWIR1})/(\rho_{green} + \rho_{SWIR1})$
AWEInsh	$4\times(\rho_{green} - \rho_{SWIR1}) - (0.25\times\rho_{NIR} + 2.75\times\rho_{SWIR2})$
AWEIsh	$\rho_{blue} + 0.25\times\rho_{green} - 1.5\times(\rho_{NIR} + \rho_{SWIR1}) - 0.25\times\rho_{SWIR2}$
WRI	$(\rho_{green} + \rho_{red})/(\rho_{NIR} + \rho_{SWIR2})$
MOWI	$\sum_{i=1}^{N} a_i \times \rho_i \quad ,a_i \in [-10,10]$
MBWI	$2\rho_{green} - \rho_{red} - \rho_{NIR} - \rho_{SWIR1} - \rho_{SWIR2}$

Table 1. Water index expressions (ρ is surface reflectance of Landsat 8 OLI image).

However, the results of index-based water extraction methods do not use all spectral potential of bands for water detection, which leads to some weaknesses. For example, the reflectance

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of confused surfaces is similar to surface water. Also, pixels with ice/snow or clouds may show a high value, which is prone to be mistaken with surface water using two-band method. Accordingly, using multi-band indices may have advantages compared with indices that use limited number of bands for identifying surface water (Wang et al. 2018; Ji et al. 2015). In recent years, some studies have been done to extend new indices for water detection. Moradi, Sahebi, and Shokri (2017) proposed Modified Optimization Water Index (MOWI) for Landsat-8 OLI/TIRS, in which they used all spectral potential of Landsat 8 for water detection on lakes and dams in Iran. Wang et al. (2018) proposed Multi-Band Water Index (MBWI) for Landsat 8 images, maximizing the spectral difference between water and non-water surfaces using pure pixels and the K-means cluster method to automatically extract surface water. Mentioned water indices are presented in Table 1. In this paper, it is attempted to develop a novel water index, focusing on salt lakes, which has not been addressed in previous studies.

2. METHODOLOGY

Salty lakes have a variety of important aesthetic, cultural, economic, recreational, scientific, conservational, and ecological values, the monitoring of which is necessary (Williams 2002; Williams 1993). Existing indices have been developed for pure water, such as dams, rivers, reservoirs and freshwater lakes. So, the main goal of this study is to develop new water extraction index, Salty Water Index (SWI), focusing on salty lakes (not pure water) using all spectral potential of Landsat 8 OLI/TIR by 30-meter spatial resolution (Table 2), considering a linear combination of bands, in which coefficients are defined by one of the proper meta-heuristic algorithms (PSO). These methods can be used for all land use classes (except building that have a geometry feature) to extend spectral index for all remote sensing optical sensors. The main steps of the proposed method are shown in Figure 1.

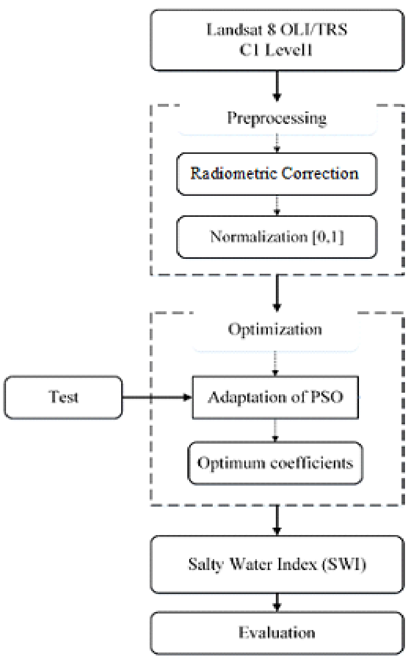

Figure 1. Methodology flowchart

Particle swarm optimization (PSO), as one of the best optimization algorithms, gives the best percentage of each band's participation in the Salty Water Index. Salty waterbody extraction is the main goal of this paper. Also, SWI uses the full spectral potential of Landsat 8 OLI/TIRS for salty water body extraction.

OLI Band	Band Name	Spatial resolution (m)
1	Coastal aerosol	30
2	Blue	30
3	Green	30
4	Red	30
5	Near IR	30
6	SWIR 1	30
7	SWIR 2 (MIR)	30
8	Panchromatic	15
9	Cirrus	30
10	Thermal Infrared (TIRS) 1	30 (100)
11	Thermal Infrared (TIRS) 2	30 (100)

Table 2. Spectral information of Landsat 8 OLI/TIR

Salty water index (SWI) is designed with the whole spectral potential of Landsat 8 images according to a linear combination of bands (Equation (1)). Each band coefficient is determined by particle swarm optimization to enhance the separability of salty water and non-water surfaces.

$$SWI = \sum_{i=1}^{N} c_i \times b_i \tag{1}$$

$N: number\ of\ bands$
$c_i: coefficient\ of\ band\ i,\ a_i \in [-5, 5]$
$b_i: band\ i$

2.1 Study Area

In order to investigate performance of the proposed method using Landsat OLI imagery, four salty lakes (Figure 2), namely the Lake Eyre in Australia, the Great Salt Lake in Utah, USA, Lake Assal in central-western Djibouti, and Lake Urmia in Iran, were chosen with a variety of climatic conditions, and different salinity, consisting of complex surface features, such as cloud, shadow surrounding the lake, water mixed with vegetation, near urban, and semi-desert condition for assessing the new index in all conditions. The required data are collected from the US Geological Survey (USGS) Global Visualization Viewer (collection 1 level-1).

2.2 Evaluation Indices

To evaluate the performance of the SWI, five accuracy measures, including overall accuracy, kappa coefficient, recall, precision, and F-score are applied. A higher recall value represents the higher ability of SWI to extract water pixels. A higher precision indicates that the algorithm has fewer errors. In the following equations, TP, FP, and FN denote the number of true positives (true detections), false positives (false detections), and false negatives (missed detections), respectively.

In Equation (6): $CN = FP + TN$, $CP = TP + FN$, $RP = TP + FP$, $RN = FN + TN$.

$$Recall = \frac{TP}{TP + FN} \tag{2}$$

$$Precision = \frac{TP}{TP + FP} \tag{3}$$

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$$F-score = 2.\frac{Precision.Recall}{Precision + Recall} \quad (4)$$

$$ACC = \frac{TP + TN}{CP + CN} \quad (5)$$

$$ACC = \frac{TP + TN}{CP + CN} \quad (6)$$

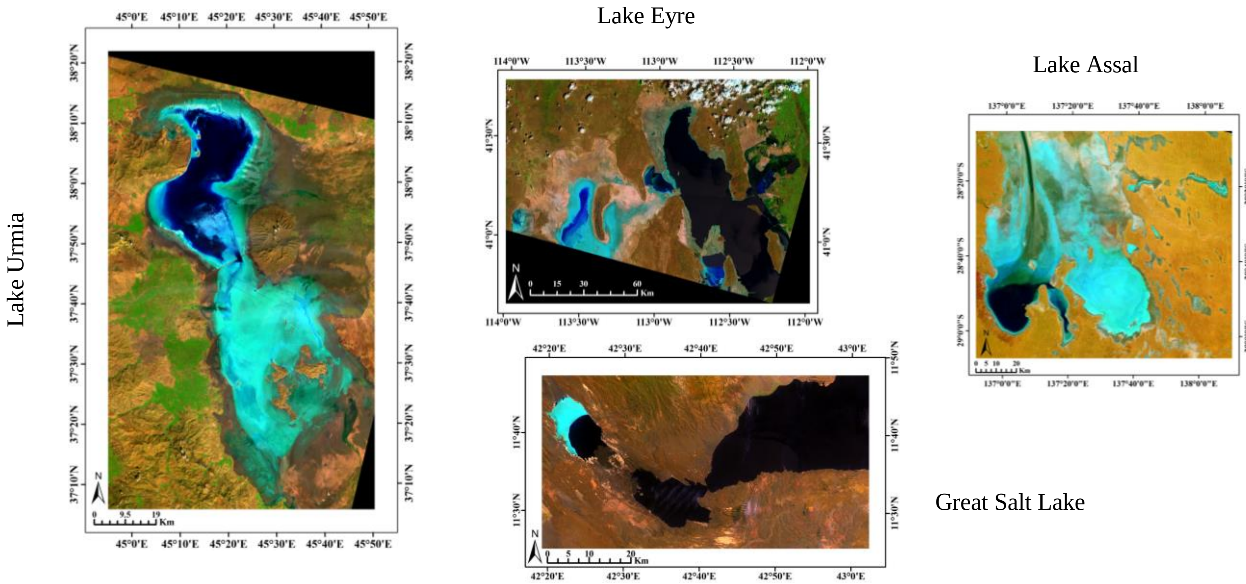

Figure 2. Image map of study areas

3. RESULTS AND DISCUSSION

3.1 Salty Water Index (SWI)

Particle swarm optimization was used to calculate the optimum band coefficient. First, the proposed method was implemented in one of the study areas by initial test data. Then, the results and improved test were evaluated. Water surfaces distinguished as no-water were added to water in test data, and no-water areas distinguished as water were added to no-water in test data to improve test data. Also, the existence of an area that has a spectral similarity is useful for generalization of the results to other case studies. Final optimum coefficients are presented in Table 3 for Salty Water Index (SWI).

Band	Coefficient	
Coastal aerosol	0.383893589646313	~ 0.38
Blue	0.681814020623350	~ 0.68
Green	2.476522955237661	~ 2.48
Red	0.577427270969090	~ 0.58
Near IR	-3.928278551159207	~ -3.93
SWIR 1	0.857986119761051	~ 0.86
SWIR2	-0.658112057243780	~ -0.66
Thermal Infrared (TIRS) 1	-0.144144133287664	~ -0.14
Thermal Infrared (TIRS) 2	0.090287462279507	~ 0.09
Cirrus	-0.767467266365048	~ -0.77

Table 3. Optimized coefficients of each band

3.2 Water Extraction Maps

The results of the proposed water index, Salty Water Index (SWI), are related to the investigations on four case study areas, i.e. Urmia Lake, Eyre Lake, Great Salt Lake and Assal Lake. Results of SWI are compared with other famous water indices like NDWI, AWEIsh, AWEInsh, MNDWI, WRI, MOWI, and MBWI. Table 4 shows the results of water detection based on overall accuracy (OA), F-score and kappa coefficient (K). Ground truth data are gathered using images and checking by google earth.

Visual examinations of Figure 3 indicated that the SWI has better accuracy than other indices at Lake Assal, where clouds were correctly classified by SWI index compared to other indices. At this test site, the worst accuracies were achieved by MNDWI, WRI and MOWI, with a kappa coefficient of 0.7. In contrast, the Kappa coefficient of MBWI, AWEIsh and SWI is greater than 0.9. Also, AWEInsh index has a poor performance to extract edge pixels of this test site (blue rectangle) and MNDWI, AWEInsh, MOWI and WRI have had misdetections in a salty area. Significant errors can be observed in figures, but some of the errors are marked as red and yellow circles. Red means pixels that could not detect water and yellow circles are misdetections.

It appeared that all indices, except for SWI, performed weakly to suppress clouds and their shadow at Great Salt Lake study area. Water surfaces could not be completely classified by MBWI index and some of them were extracted as no-water. Visual inspection of Figure 4 clearly shows that MNDWI, $AWEI_{nsh}$ and WRI have had misdetections in salty area of this study area (yellow circle). SWI and NDWI indices have better results than other indices. In this regard, SWI has the best result with an overall accuracy of 98.41%.

The results showed the poor operation of AWEInsh with an overall accuracy of 82.52% on Eyre Lake. As shown in Figure 5, this index has wrongly detected the salty area as a water body. SWI and NDWI indices had nearly the same results due to the lack of cloud and shadow surfaces. Also, SWI had the best result with an overall accuracy of 98.86% and a kappa coefficient of 0.98. Evaluation of the performance of indices shows that the results of AWEI, WRI, and MBWI were similar.

Indices	Lake Assal			Great Salt Lake			Lake Eyre			Lake Urmia		
	OA	F-score	K	OA	F-score	K	OA	F-score	K	OA	F-score	K
SWI	99.54	99.53	0.99	98.41	98.66	0.97	98.86	98.92	0.98	98.68	98.72	0.97
NDWI	90.34	90.55	0.81	97.80	98.18	0.95	98.52	98.56	0.97	91.73	91.51	0.83
MNDWI	86.86	87.85	0.74	87.16	90.23	0.72	91.37	91.61	0.83	88.97	89.38	0.78
$AWEI_{nsh}$	92.19	92.67	0.84	86.52	89.82	0.7	82.52	84.38	0.65	75.19	80.32	0.50
$AWEI_{sh}$	96.37	96.45	0.93	92.29	93.88	0.83	95.35	95.29	0.91	92.17	91.83	0.84
WRI	86.59	87.63	0.73	89.91	92.19	0.78	95.23	95.17	0.90	95.37	95.29	0.91
MOWI	88.06	88.98	0.76	93	94.17	0.85	96.71	96.72	0.93	95.15	95.08	0.90
MBWI	96.44	96.52	0.93	90.44	92.09	0.8	95.12	95.05	0.90	96.47	96.45	0.93

Table 4. Accuracy of the water indices by test sites

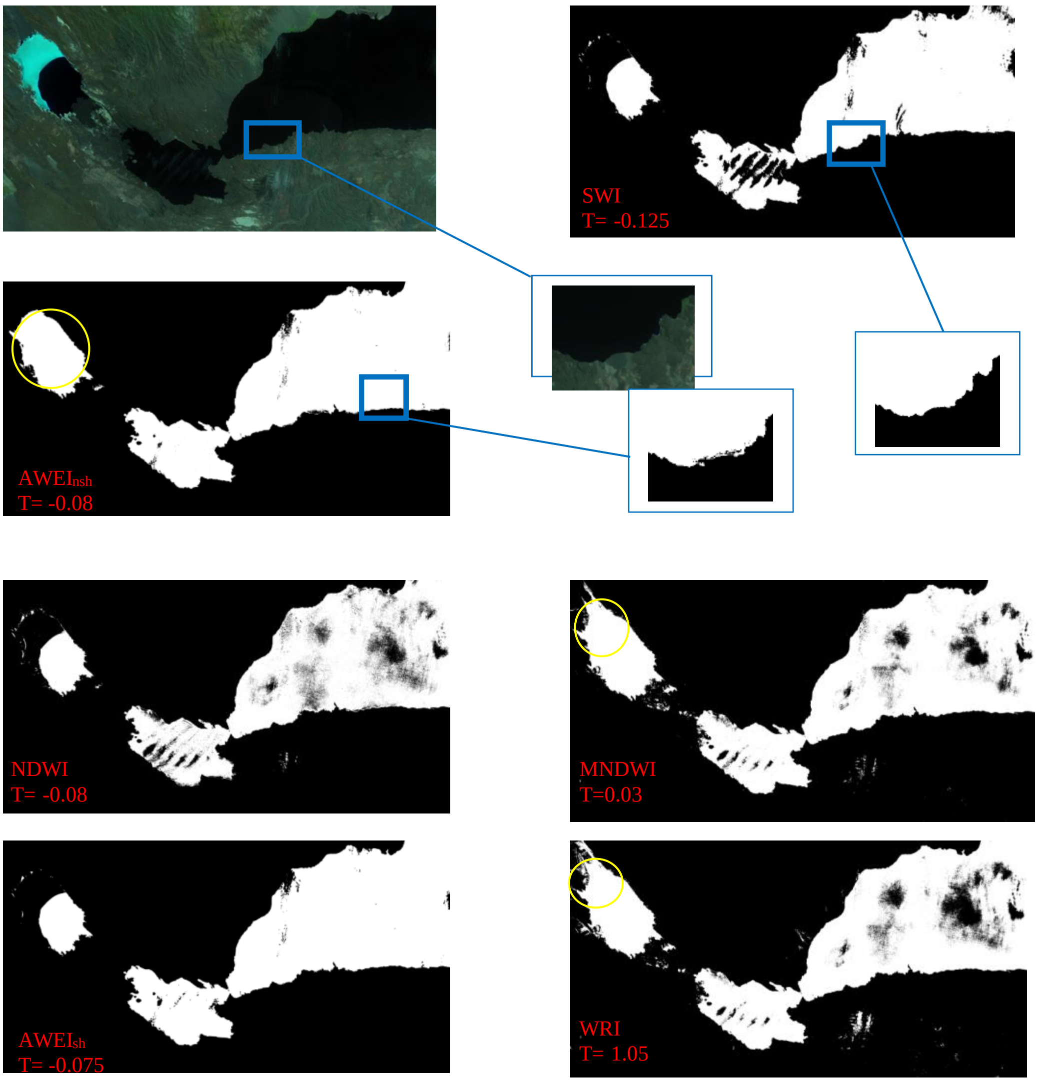

Figure 3. Water extraction results using different indices at Lake Assal

As is shown in Figure 6, shadows were extracted as water by NDWI at Lake Urmia in Iran (blue rectangle). SWI, unlike MBWI, detected too small water bodies with a width less than 3 pixels (green rectangle). At this study area, it's clearly visible that the accuracy difference between AWEInsh and SWI was significant. SWI had better results than other indices with an overall accuracy of 98.68%. AWEInsh had the worst results in all test sites, except Lake Assal, due to the extraction of salty areas.

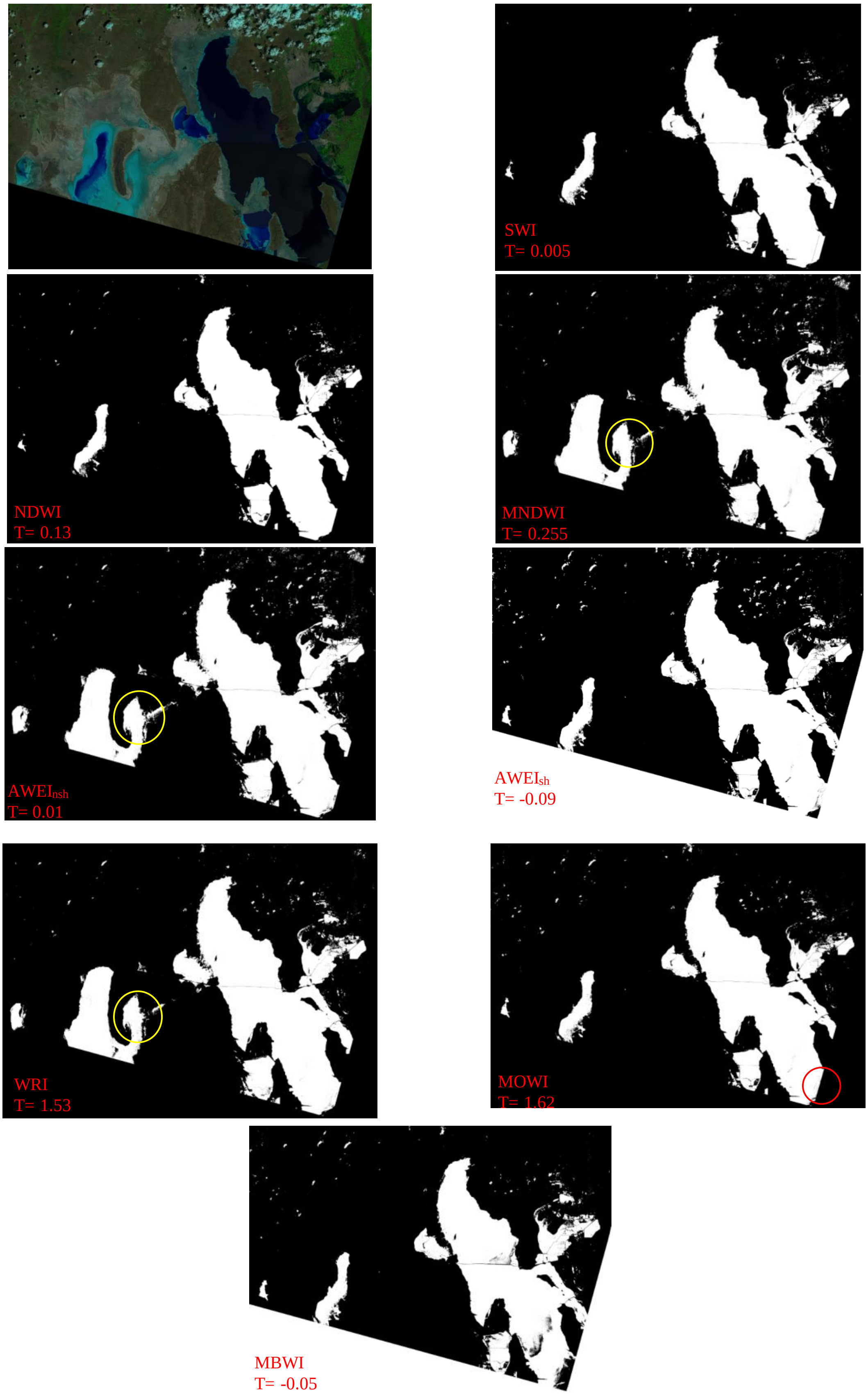

Figure 4. Water extraction results using different indices at Great Salt Lake

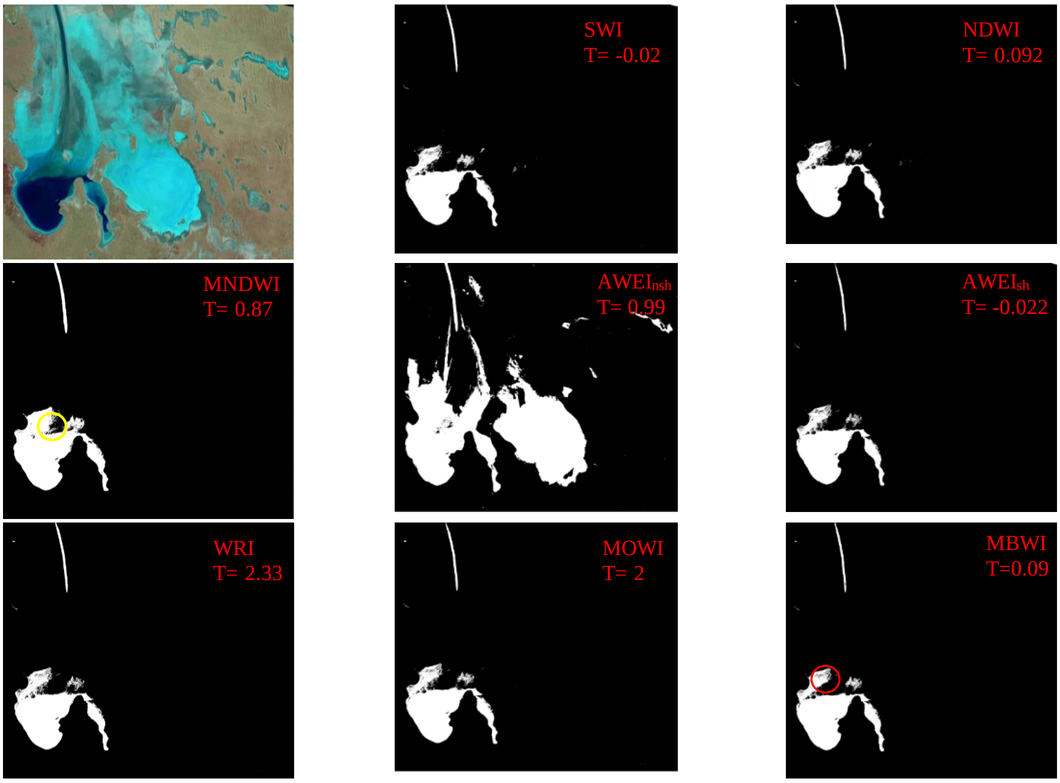

Figure 5. Water extraction results using different indices at Eyre Lake

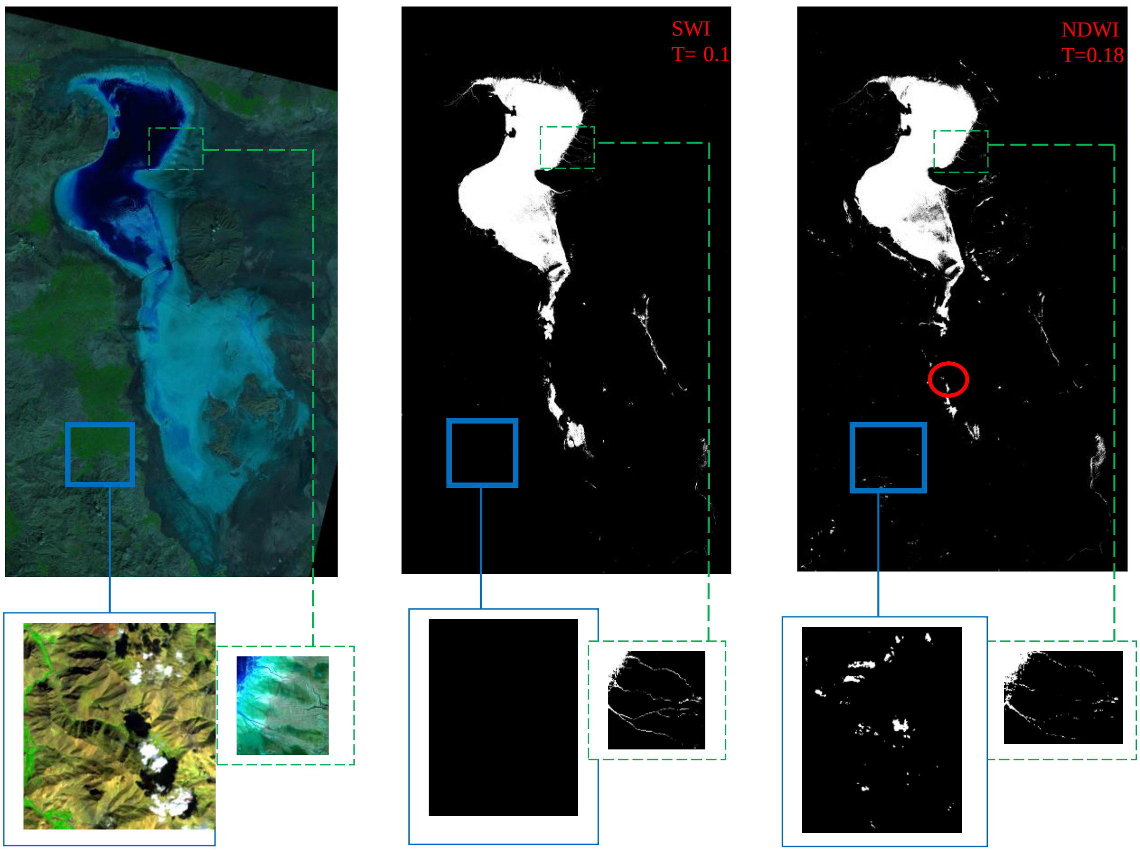

Figure 6. Water extraction results using different indices at Lake Urmia

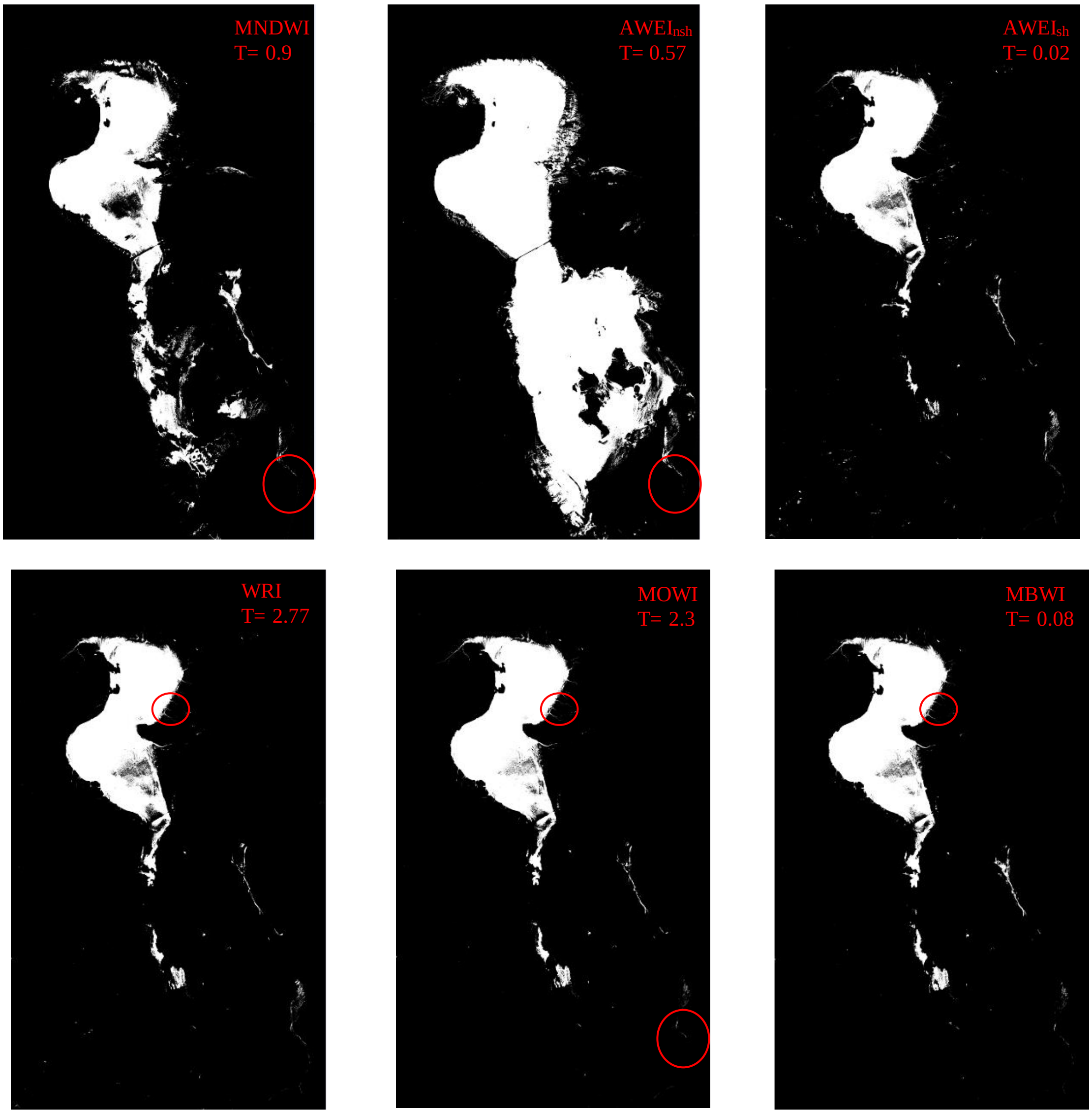

Figure 6. (continued)

Standard Deviation to mean ratio is another criterion for assessing indices.. Lower ratio indicates better efficiency. Figure 7 shows the Standard Deviation to mean ratio of overall accuracy, F-score and kappa coefficient in four case study areas. As can be seen, the minimum value of this ratio is related to SWI.

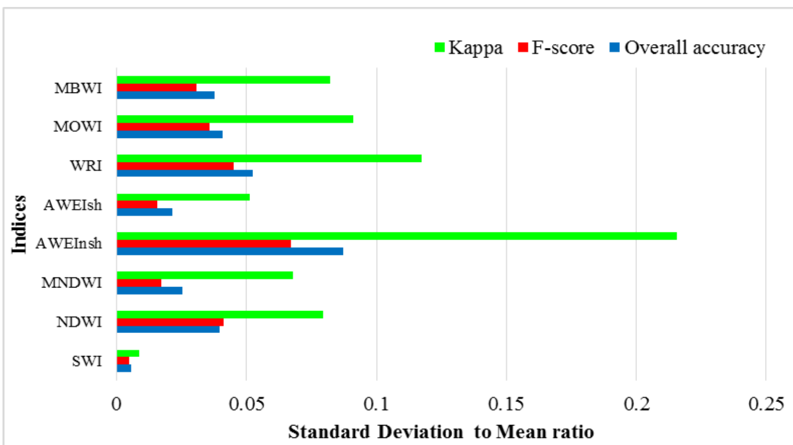

Figure 7. Standard Deviation to mean ratio of overall accuracy, F-score and kappa coefficient in four case study areas

3.3 Effectiveness Criteria

The effect of each band on water extraction is calculated with the criterion of effectiveness. This method of band performance analysis has been defined by Moradi, Sahebi, and Ghayourmanesh (2018) to examine the impact of the features on change detection. In this index, each band or feature is eliminated and the performance of each band is computed with the remaining bands or features. Effectiveness is the difference of accuracy in the optimal form, which is the same accuracy of SWI index (optimum overall accuracy), and the accuracy in the absence of each band (Removed Optimum Overall Accuracy) (Equation (7)). The value of effectiveness for overall accuracy is given in Figure 8. Higher E values indicate the greater impact and importance of the corresponding band in water extraction, especially salty water.

$$E_{B_i} = OOA - ROOA \tag{7}$$

According to Figure 8, it can be concluded that some bands have highly affected water detection results in all conditions, while other bands depend on the characteristics and environmental conditions of the case study. The green (band 3) and near IR (band 5) of Landsat 8 are very effective in all imagery conditions. In addition, the cirrus band in areas with cirrus cloud, such as Lake Assal, the TIRS1 band at Great Salt Lake, the SWIR 2 and blue bands at Lake Eyre as well as blue and red bands at Lake Urmia study area are of high effectiveness. This subject shows the effectiveness of the design of Landsat 8 bands, as the latest satellite of the Landsat Satellite series. In this series, various bands help detect the desired phenomena and land use and land classes in different conditions. On the other hand, the above results indicate that the higher band coefficient or the positive sign does not show the higher performance.

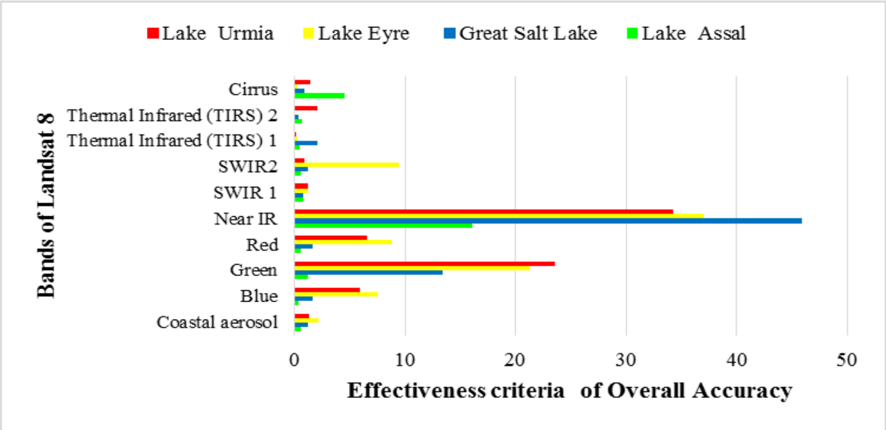

Figure 8. Results of effectiveness criteria based on SWI

4. CONCLUSION

In this study, a novel index called SWI (Salty Water Index) was proposed for surface salty water extraction from Landsat 8 OLI imagery. The proposed strategy was successfully used in four different test sites, including Lake Assal, Great Salt Lake, Eyre Lake, and Lake Urmia. Results of SWI are compared with seven used water indices, i.e. NDWI, $AWEI_{sh}$, $AWEI_{nsh}$, MNDWI, WRI, MOWI, and MBWI.

SWI improved accuracy in areas where there were clouds and shadow, and significantly suppressed them. This new method did not have misdetections in the salty area compared to MNDWI, $AWEI_{nsh}$ and WRI indices. Also, SWI had a proper performance to extract edge pixels compared to $AWEI_{nsh}$. This new method would also be suitable to extract too small water bodies. The proposed index is ready to be applied in other salty lakes in the world. Also, effectiveness results showed the high spectral potentials of Landsat 8 for water detection, which was properly used by the proposed method. Finally, the proposed method can be applied for other classes and other sensors for new indices that use full spectral potential of sensors.

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