Emirates Journal for Engineering Research

Volume 27 | Issue 1 Article 1

12-25-2021

# Environmental Impacts of Seawater Desalination on the Marine Environment in the Kingdom of Bahrain

Waleed Al-Zubari
waleed@agu.edu.bh

Alaa ElSadek
*Arabian Gulf University*, alaasa@agu.edu.bh

Mohamed Khadim
elhomed@hotmail.com

Recommended Citation
Al-Zubari, Waleed; ElSadek, Alaa; and Khadim, Mohamed (2021) "Environmental Impacts of Seawater Desalination on the Marine Environment in the Kingdom of Bahrain," *Emirates Journal for Engineering Research*: Vol. 27 : Iss. 1 , Article 1.
Available at: https://scholarworks.uaeu.ac.ae/ejer/vol27/iss1/1

# ENVIRONMENTAL IMPACTS OF SEAWATER DESALINATION ON THE MARINE ENVIRONMENT IN THE KINGDOM OF BAHRAIN

**Waleed K Al-Zubari[1], Alaa A El-Sadek[2] and Mohamed J Khadim[3]**

[1] Prof., Water Resources Management Program, College of Graduate Studies, Arabian Gulf University, Manama, Kingdom of Bahrain, waleed@agu.edu.bh
[2] Prof., Water Resources Management Program, College of Graduate Studies, Arabian Gulf University, Manama, Kingdom of Bahrain, alaasa@agu.edu.bh
[3] Eng., Water Resources Management Program, College of Graduate Studies, Arabian Gulf University, Manama, Kingdom of Bahrain, elhomed@hotmail.com

*(Received 3rd December 2020 and accepted on 25th December 2021)*

# التأثيرات البيئية لتحلية مياه البحر على البيئة البحرية في مملكة البحرين

## ملخص

يتمثل التحدي الرئيسي الذي يواجه البحرين في تخطيط وإدارة المياه في كيفية تحقيق التوازن بين توافر المياه واستخدام المياه على المدى الطويل في مواجهة الطلبات المتزايدة بأقل التكاليف الاقتصادية والبيئية ودون التأثير على التنمية الاجتماعية والاقتصادية. ولتلبية الطلبات البلدية المتزايدة على المياه، أصبحت تحلية المياه أمراً لا مفر منه، وهو ما يصاحبه تكاليف مالية واقتصادية وبيئية كبيرة. في هذا البحث، تم تقييم التأثير البيئي لتحلية مياه البحر على البيئة البحرية المحيطة لمحطة تحلية مياه حكومية تعمل بنظام التبخير الوميضي متعدد المراحل (محطة سترا للطاقة والمياه(SPWS)). استخدم التقييم عدداً من المؤشرات البيئية، وهي درجة الحرارة والملوحة (مجموع الأملاح الكلية الذائبة) في منطقة مصب محطة تحلية المياه، وتضمن مسحاً ميدانياً لتوصيف منطقة مصب محطة تحلية المياه، ومحاكاة لمنطقة المصب باستخدام النموذج الهيدروديناميكي CORMIX بعد معايرته بالبيانات الحقلية، وتقييم سيناريوهات التخفيف. وقد تم توصيف ومحاكاة درجة الحرارة المرتفعة وملوحة المياه المنصرفة في فصل الشتاء، حيث يحدث أقصى تأثير حراري. أوضحت المحاكاة أن درجة حرارة المياه المنصرفة في حدود المواصفات القياسية لمنطقة الخلط بالبحرين. تنخفض درجة حرارة المياه المنصرفة إلى درجة حرارة البحر المحيطة خلال 37 دقيقة بعد الصرف وعلى مسافة 350 متراً من المصب. كما تنخفض ملوحة المياه المنصرفة إلى ملوحة مياه البحر المحيطة خلال 41 دقيقة وعلى مسافة حوالي 390 متر من المصب. تم تقييم فعالية خيار التخفيف في خلط مياه التبريد المستخدمة في إنتاج الطاقة مع المياه المنصرفة خلال فصل الشتاء، ووجد أنها تقلل تأثير درجة الحرارة بنسبة 30٪ والملوحة بنسبة 38٪ بالمقارنة مع الظروف الحالية. وتمت التوصية باستخدام مؤشرات بيئية كمية أخرى لتوصيف وتقييم تأثير تحلية المياه على البيئة البحرية، مثل المواد الكيميائية في المياه المنصرفة، وتلوث الهواء، والمجتمعات البيولوجية، والتي تستخدم في تقييم الآثار البيئية لتحلية المياه، تصميم وتنفيذ برنامج مراقبة دوري لنوعية مياه البحر في المنطقة القريبة من المصب ومنطقة الخلط، وإجراء دراسات تحقيق وتقييم مماثلة على جميع محطات تحلية المياه الأخرى في البحرين.

## Abstract

The main water planning and management challenge facing Bahrain is in how to balance water availability and water use on a long-term basis in the face of increasing demands under the least economic and environmental costs and without endangering socio-economic development. To meet escalating municipal water demands desalination is becoming inevitable, which is associated with substantial financial, economic, and environmental costs. In this research, the environmental impact of seawater desalination on the surrounding marine environment is assessed at a government-owned MSF desalination plant (Sitra Power and

Water Station (SPWS)). The assessment used a number of environmental indicators, namely temperature and salinity (TDS) at the desalination plant outfall area, and included a field survey to characterize the outfall area of the desalination plant, simulation modeling of the outfall area using CORMIX hydrodynamic model after its calibration by field data, and investigating mitigation scenarios. Characterization and simulation of elevated temperature and salinity of brine discharge was made for the winter season, where the maximum thermal impact occurs. The simulation indicated that the brine temperature is within Bahrain Mixing Zone Standards. The brine plume elevated temperature drops to ambient temperature within 37 minutes after traveling a distance of 350 meters downstream. The brine plume elevated salinity drops to the ambient seawater salinity within 41 minutes and a distance of about 390 m downstream. The effectiveness of a technical mitigation option of mixing of power cooling water with brine during the winter season was assessed and was found to have the potential of reducing the impact of the temperature by 30% and salinity by 38% in comparison to the current conditions. It is recommended that other quantifiable environmental indicators to characterize and assess desalination impacts on the marine environment, such as brine chemicals, air pollution, and biological communities, are used in assessing the environmental impacts of desalination; a regular monitoring program of seawater quality in the Near Field Region (NFR) and the Regulatory Mixing Zone (RMZ) is designed and implemented, and similar investigative and assessment studies are conducted on all the other desalination plants in Bahrain.

*Keywords: Desalination; CORMIX; Brine; Modeling; Mitigation scenario*

## 1. INTRODUCTION

Since the mid 1970s, and as a result of the continuous increase in water demands in the municipal sector on one hand, and groundwater deterioration on the other, the Government of Bahrain has resorted to desalination. Now, Bahrain has a well-developed water utility sector with several large desalination plants that provide the water requirements of the entire drinking water sector in the country. Desalination sector has grown rapidly alongside Bahrain's socio-economic development. Currently there are 5 desalination plants located along the eastern coast of Bahrain. In order to meet the rapid increase in municipal water demands, the Government of Bahrain has started in the early 2000 to rely on purchasing desalinated water from the private sector. Currently, there are three private sector desalination plants that are supplying the water authorities with its municipal water supply requirements. These are Al-Hidd, Al-Dur, and Aluminium Bahrain (ALBA). The details of these desalination plants are indicated in Table (1). The Government still owns and operates two desalination plants (Sitra and Ras Abu Jarjur). In 2012, the total desalination capacity in the country has reached about 870,000 m3/day (315 Million m3/yr). The total production of desalinated water in 2014 was about 713,570 m3/day (260 Mm3/yr).

Table 1. Daily production capacity of desalination plants in Bahrain.

| No. | Plant | Commissioning Date | Technology Used | No. of Units | Capacity 1000 m3/d | Feed Water | Ownership/ Management | Ratio of Brine |
|---|---|---|---|---|---|---|---|---|
| 1 | Sitra (SPWS) | 1975 | Multistage-Flash (MSF) | 6 | 113.6 | Seawater | Government | 11X produced |
| 2 | Ras Abu Jarjur (RAJ) | 1984 | Reverse Osmosis (RO) | 10 | 77.3 | Brackish Groundwater | Government | 1.4X produced |
| 3 | Ad Dur (ADUR) | 1990 | Reverse Osmosis (RO) | 8 | 18.2 | Seawater | Government | 2.5X produced |
| 4 | Hidd | 1999 | Multistage-Flash (MSF) and Multi-Effect Distillation (MED) | 14 (4 MSF and 10 MED) | 409.1 | Seawater | Privatized (entire production purchased) | 2X produced<br>2.5X produced |
| 5 | Alba | 2002 | Multi-Effect Distillation (MED) | 4 | 31.8 | Seawater | Private (part of the production purchased) | Not available |
| 6 | Al-DUR | 2012 | Reverse Osmosis (RO) | 26 | 220.0 | Seawater | Private (entire production purchased) | 2.5X produced |
| Total Desalination capacity | | | | | 870 | | | |

Data Source: Electricity and Water Authority (EWA).
Note: Al Dur SWRO, owned by EWA, is no more existing as a production facility; currently it is mothballed until a time that EWA may refurbish, upgrade it, or replace it by a new plant (plant #6).

Until the mid 1980s, the municipal sector relied mainly on groundwater and was augmented by desalinated water in small ratios. However, with the major expansion in desalination plants, desalinated water has become the main component of municipal water supply with little augmentation by groundwater. Figure (1) shows the continuous increase of desalinated water share in the municipal water supply. Desalinated water ratio has risen from 7% in 1980 to 90% in 2014, which significantly improved the quality of the municipal water supply in the Kingdom.

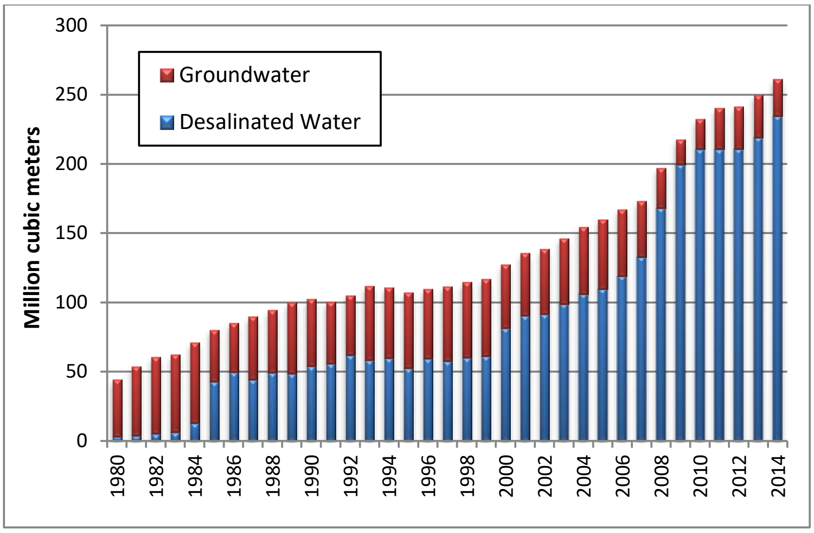

Figure 1. Desalinated water and groundwater (municipal sector) and distilled water development in Bahrain (1980-2014) (data source: EWA).

In view of the current trends in population and urbanization growth rates and their associated municipal water requirements desalination will continue to be the main source of water to be relied on by the municipal water authorities in Bahrain, and an expansion in the desalination capacity and production is inevitable to meet these demands. The expansion in desalination will be associated with financial, economic, environmental, and eventually social costs and impacts, which need to be assessed, quantified, and mitigated to the maximum possible level.

From a management perspective, there are two approaches that need to be taken to minimize desalination impacts and costs; the first approach is to improve the efficiency of the municipal water system in both the supply and demand sides (i.e., use and supply efficiencies, recycling, and reuse) in order to reduce the overall water requirements and thus reducing desalination production and its associated financial, economic and environmental costs. Many of the financial, economic, and environmental costs associated with desalination and municipal water supply systems have been addressed in Bahrain and appropriate management interventions for their minimization have been proposed [1].

The second approach, which is complementary to the first approach, is to implement scientific and technological means to mitigate the impacts of desalination plants on their surrounding environment. This approach has received little attention in Bahrain. This approach includes reduction of the source concentrations and loads by proper mitigation measures within the desalination plant or proper intake and pre-treatment technologies, and implementing enhanced mixing technologies for the discharged brine.

For a new desalination plants, basic knowledge of the resulting concentration distributions allows for an impact assessment and design optimization, where the concentration distribution will depend on the sitting of the outfall, the amount of mixing and the transport capacities of the prevailing currents [2]. Such impact assessment and optimized brine disposal design is typically made using simulation modeling where various disposal systems (e.g., onshore surface open channel, offshore submerged single port or multiport) are evaluated to select the optimal environmental disposal system which can mitigate the adverse impacts of brine on the marine ecosystem as much as possible in the worst seawater conditions (e.g., [3][4]). On the other hand, for an existing desalination plant, a typical environmental impact assessment and mitigation procedures would involve outfall site characterization and modeling approach to improve the design of the discharge such that effluent impacts are minimized. Such approach would require the followings steps: the impact of a given desalination plant on the surrounding marine environment is characterized in the vicinity of the brine discharge area; then, the results of the characterization stage are used to calibrate and develop a hydrodynamic simulation model for the desalination plant and its surrounding marine environment; once the simulation model is calibrated to satisfactorily represent the existing system of the desalination plant and its surrounding marine area, it is used to investigate the effectiveness of various proposed mitigation options.

The objective of this research is to assessing the environmental impacts of desalination plants discharge on the marine environment in Bahrain using a government-owned thermal (MSF) desalination plant as a case study. This is achieved through field characterization of the outfall area of the desalination plant, hydrodynamic simulation of the outfall area using Cornell Mixing Zone Expert System (CORMIX), and using the developed model in assessing the effectiveness of potential mitigation scenarios.

## 2. MATERIALS AND METHODS

The study's methodology consisted of building a representative simulation model for the outfall area of the MSF desalination plant by calibration against measured field data of salinity and temperature in the surrounding seawater. The calibrated model parameters were the flowrates and effluent characteristics of the desalination plant, and the simulation results were compared with measured data (temperature and salinity) in the field at 25 cm and 1 m below the sea surface. The Model calibration was carried out for the winter season conditions as the field measurements were made during this season, and where the differences in the temperature during the winter season (20ºC) are more pronounced than the summer (7ºC). Then, the calibrated model is used to analyze the spatial distribution of the temperature and salinity plumes of the brine discharged from the desalination plant, and investigate technical options to mitigate the brine environmental impact and ensure regulatory compliance. The followings are brief description of the desalination power plant and the simulation model used.

### 2.1 SITRA POWER AND WATER STATION (SPWS)

The study was conducted on the outfall area of the SPWS. SPWS has three phases (Table 2), two seawater intakes and four outfall culverts. A flow diagram of the intake and outfall is shown in Figure (2; note only three outfall culverts are shown in the figure). The outfall area is being constrained by two jetties (Figure 3). These Jetties were constructed to minimize the spread of brine plume, and thus minimize the area of ecological impact, and in the case of the north jetty to limit the intrusion of the brine into the seawater intake areas [5].

Table 2. Phases of Sitra Power and Water Station (SPWS)

| Phase | Commissioning Year | Technology Used | No. of Units | Desalinated Water (1000 m$^3$/day) |
|---|---|---|---|---|
| I | 1975 | MSF | 2 | 22.73 |
| II | 1984 | MSF | 1 | 22.73 |
| III | 1984/1985 | MSF | 3 | 68.2 (operated at 90°C TBT)<br>92.7 (operated at 110°C TBT) |

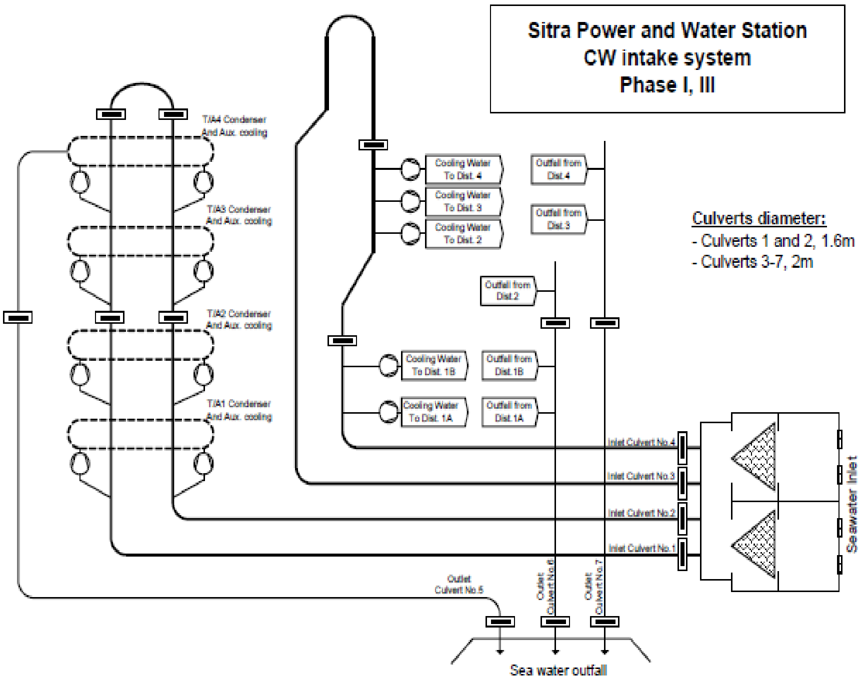

Figure 2. Seawater intake and outfall of SPWS

Figure 3. Locations of sampling points

### 2.2 THE CORNELL MIXING ZONE EXPERT SYSTEM (CORMIX)

The SPWS and its outfall area is modeled using the Cornell Mixing Zone Expert System (CORMIX) software [6], which is typically used for the analysis, prediction, and design of the outfall mixing zones resulting from the discharge of aqueous pollutants into diverse water bodies. It contains mathematical models of point source discharge mixing within an intelligent computer-aided-design interface. The main input data required for the CORMIX systems are the discharge configurations and discharge site information, the ambient conditions and pollutant characteristics. The most important factors that can influence the mixing or dilution of the plume are the ambient depth, ambient velocity and effluent discharge velocity [6]. It should be noted that the four outfall culverts were modeled as one outfall culvert using the total discharge from the four.

## 3. RESULTS AND DISCUSSION

### 3.1 MODEL CALIBRATION

The CORMIX model was calibrated against field data. A total of 18 sampling points were used to characterize the seawater temperature and salinity at the outfall area of SPWS, which are used in the calibration of the model. The locations of the sampling points are shown in Figure (3). The locations of the sampling points were determined using a GPS instrument (Garmin). Temperature (in degree centigrade) and salinity (in total dissolved Solids (TDS)) were measured at these spot sampling points in the field using Marine Water Quality Monitor (YSI) instrument. The design of the sampling points was made in the form of a grid to ensure full coverage of the spatial distribution of the outfall plume between the two barriers. Sampling points X1 to X16 represent the outfall area, while both points X17 (desalination plant feed-water side) and X18 (outfall side) represent the ambient conditions of the area.

Although the sampling of the outfall area was made for low and high tide conditions, only the latter was used in the calibration of the model. This is due to that the outfall areas and its surroundings are relatively shallow and does not exceed 1.5 meters, with some areas appear at the surface during low tides. Sampling and measurements were taken at 25 cm and 1 m below the surface of the water column during both high and low tide (1.65 m and 0.96 m, respectively). The sampling for low and high tide was made on the same day (21/02/2013, 08:30 am and 14:42 pm). Model calibration using the measured data was carried out for the winter season conditions as the field sampling was made during this season. Figures (4) and (5) show comparisons between the simulated model results and the measured field data at 25 cm and 1 m below the surface of the water column during high tide for the temperature and salinity, respectively.

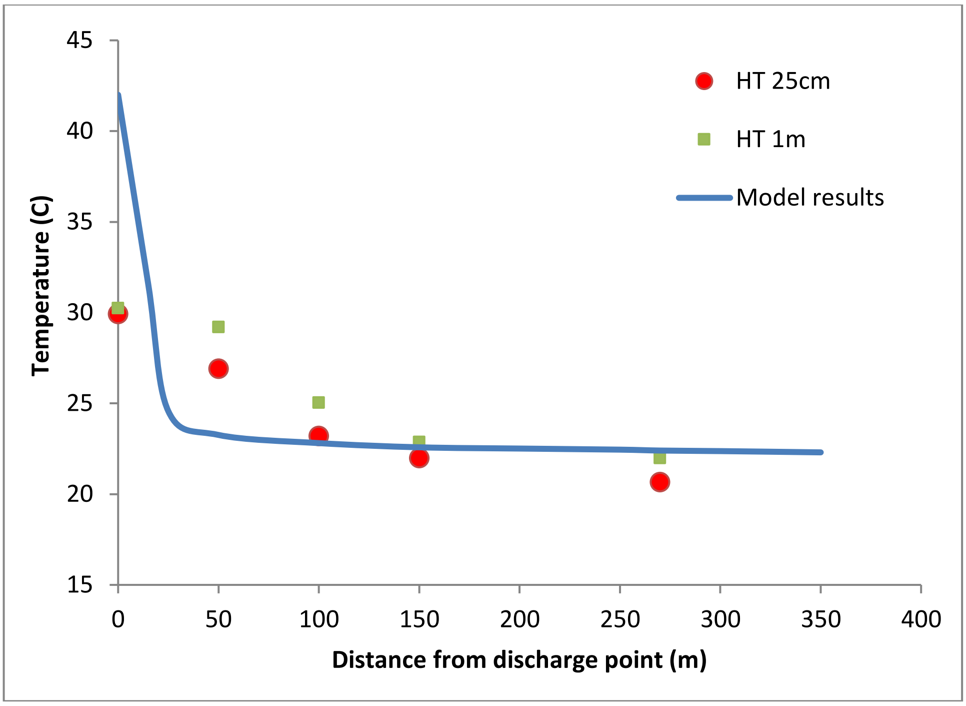

Figure 4. Simulated and measured temperature at 25 cm and 1m during high tide

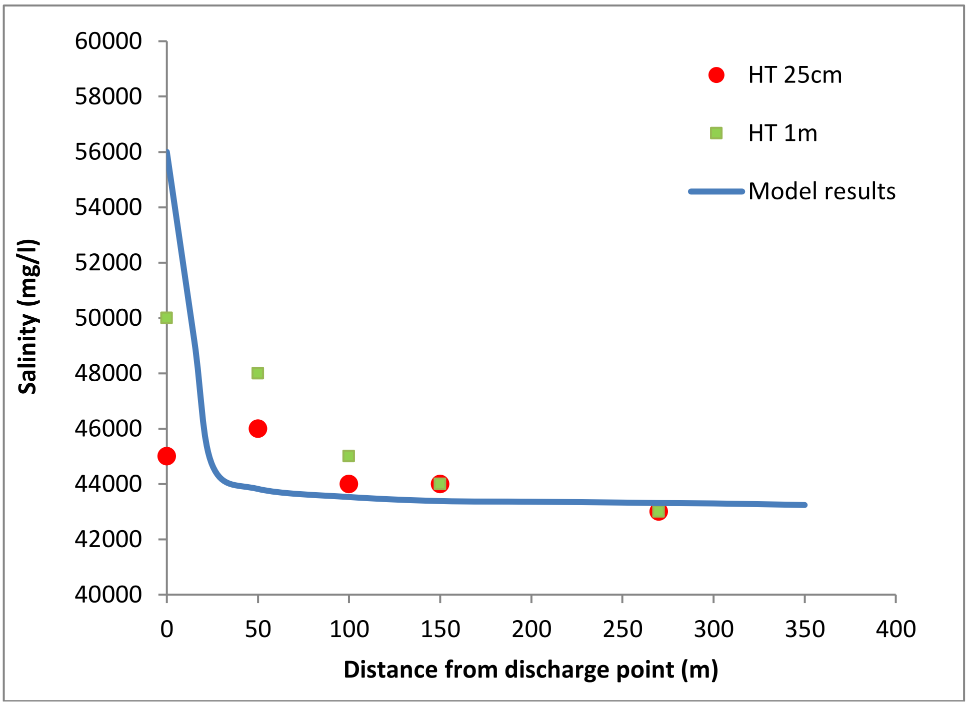

Figure 5. Simulated and measured TDS at 25cm and 1m during high tide

### 3.2 STATISTICAL ANALYSIS

The qualitative judgment of when the model performance is good is a subjective matter [7]. Therefore statistical criteria are used for the quantitative judgment [8]. Statistical based criteria provide a more objective method for evaluating the performance of the models [9]. In this study the following statistical criteria were used to evaluate the performance of the CORMIX model (refer to Annex A for the details of the statistical criteria):

- Relative Root Mean Square Error (RRMSE)
- Goodness of Fit ($R^2$)

The statistical performance analyzers calculated between the measured and the simulated values for the temperature and TDS at 25 cm and 1 m during high tide are shown in Table (3). By comparing the results shown in Table (2) with the characteristic of the different statistical criteria shown in Table (A-

1), the statistical performance indicates a good agreement between measured and simulated temperature and TDS. The results of the statistical analysis indicated that the model can be used as a good simulation tool to predict the hydrodynamics of the brine discharge into the sea.

Table 3. Statistical performance analyzers calculated between measured and simulated values for temperature and TDS at 25 cm and 1 m during high tide.

| Year | RRMSE | $R^2$ |
|---|---|---|
| Simulated and measured Temperature at 25 cm | 0.119 | 0.718 |
| Simulated and measured Temperature at 1m | 0.137 | 0.451 |
| Simulated and measured TDS at 25cm | 0.074 | 0.145 |
| Simulated and measured TDS at 1m | 0.048 | 0.650 |

## 3.3 ANALYSIS OF BRINE DISCHARGE FROM SPWS IN WINTER SEASON

### 3.3.1 ANALYSIS OF ELEVATED THERMAL DISCHARGE

An average sea water temperature of 22°C is used to represent this period, while ambient salinity is taken at 43,000 mg/L. The ambient density is calculated at 1029.98 kg/m$^3$, while the brine discharge density is calculated at 1031.07 kg/m$^3$. The discharge flow rate for this simulation was 10 m$^3$/sec, with desalination plant production of 1.05 m$^3$/sec.

The Near Field Region (NFR) is within 0.56 m from the discharge point and no changes will occur in this region (dilution = 1). The plume cumulative travel time up to the end of NFR is 54.8 sec. As the effluent density is greater than the surrounding ambient water density at the discharge level, the effluent is negatively buoyant and will tend to sink towards the bottom. The simulated results at the NFR boundary are summarized in Table (4).

Table 4: NFR characteristics

| | |
|---|---|
| Temperature at the edge of NFR | 20°C above ambient |
| Dilution at the edge of NFR | 1 |
| NFR location | X: 0.56 m, Y: 77.55 m, Z: 2.71 m |
| NFR dimension | Half width: 1.79 m, Thickness: 2.71 m |
| Cumulative travel time | 54.81 sec |

The simulated results were compared with the mixing zone water quality standards of the Kingdom of Bahrain, which states that there should be no thermal alteration within 100 m from the shoreline, which would cause temperature to deviate from ambient temperature by more than 3°C [10][11]. The results indicated that the brine thermal discharge is within the standards limit. The results also showed that the plume elevated temperature drops down to the ambient temperature in approximately 37 minutes while covering a distance of 350 meters downstream as shown in Figure (6). After that the plume will proceed down the slope without transition to far field as shown in Figure (7). The plume conditions at the boundary of Regulatory Mixing Zone (RMZ) are presented in Table (5). At the end of RMZ (100 m from the discharge outlet), the temperature is almost 0.5°C above the ambient. The plume cumulative travel time to the end of this zone is 1050 sec.

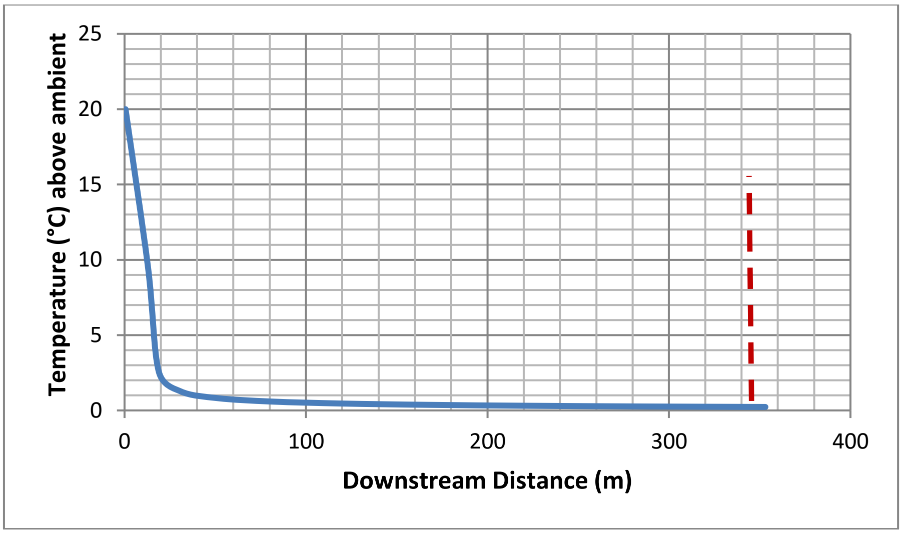

Figure 6. Simulation of Temperature downstream

Table 5: RMZ characteristics

| | |
|---|---|
| Temperature at the edge of RMZ | 0.513006°C above ambient |
| Dilution at the edge of RMZ | 39 |
| RMZlocation | X: 100 m, Y: -631.95 m, Z: -22.07 m |
| RMZdimension | Half width: 1.86 m, Thickness: 2.73 m |
| Cumulative travel time | 1049.23 sec |

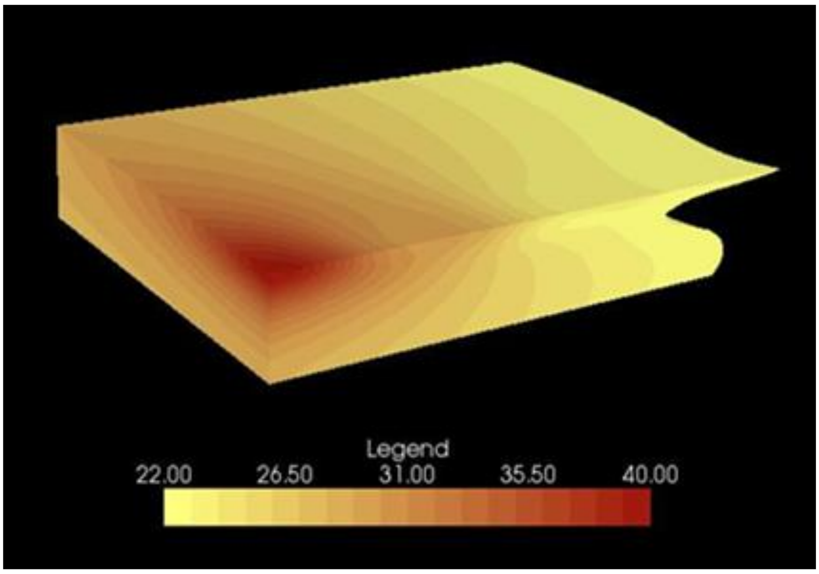

Figure 7. A 3-Dimensional view of the simulated temperature plume, in °C.

### 3.3.2 ANALYSIS OF ELEVATED TOTAL DISSOLVED SOLID (TDS)

The simulated TDS at the outfall area are illustrated in Figure (8). The results showed that at the beginning of the brine discharge, the mixing and dilution of TDS is relatively fast, up to a distance of 16 meters, downstream. After this distance, the plume travels slowly in the downstream direction and experiences a gradual dilution/mixing in that region. The results also showed that the plume elevated TDS drops down to the ambient TDS in approximately 41 minutes while covering a distance of 390 meters downstream. For the concentrated brine discharge it takes about 17 minutes to dilute its concentration from 13,000 mg/L above the ambient TDS to 240 mg/L above the ambient level at the end of RMZ (100 meters from the discharge point). The predicted results at the RMZ boundary are summarized in Table (6). The distribution of the TDS values along the downstream distance is shown in Figure (9).

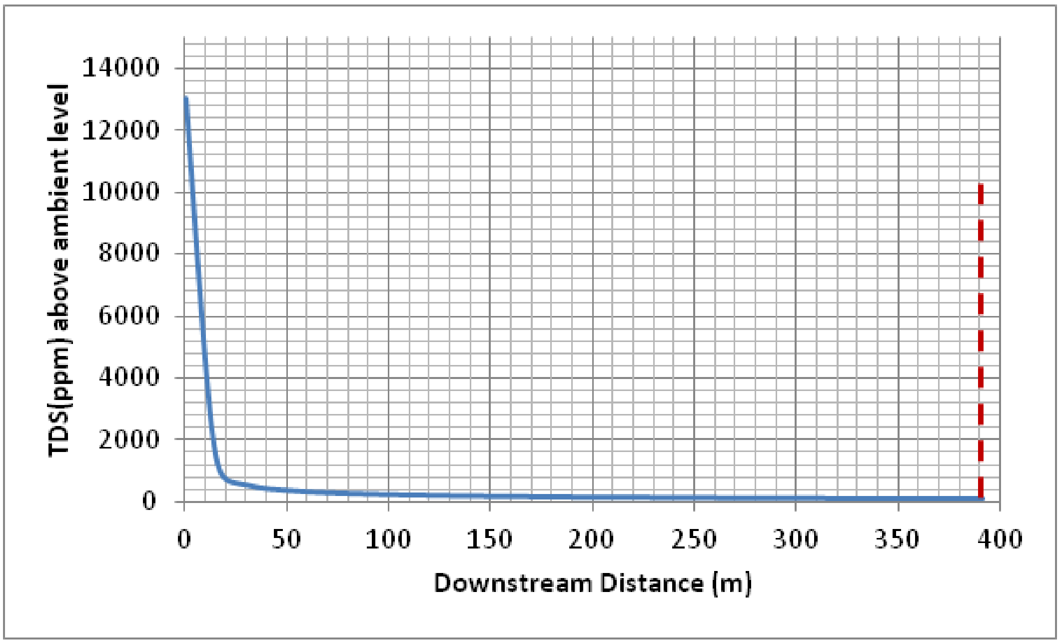

Figure 8. Total Dissolved Solid drop vs. downstream distance

Table 6: RMZ characteristics

| | |
|---|---|
| TDS at the edge of RMZ | 240 mg/L above ambient |
| Dilution at the edge of RMZ | 54 |
| RMZ location | X: 100 m |
| RMZ dimension | Half width: 52.25 m, Thickness: 21.97 m |
| Cumulative travel time | 1037.93 sec |

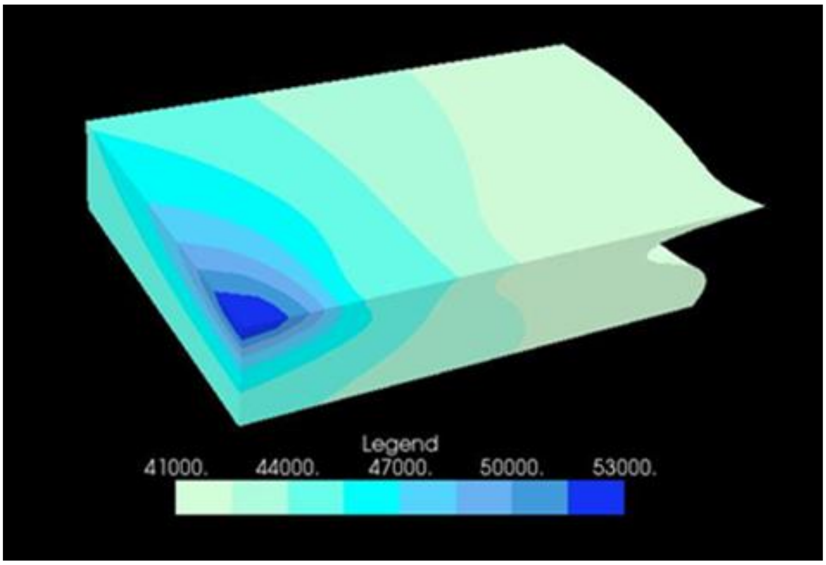

Figure 9. A 3-Dimensional view of the simulated salinity (TDS) plume, in mg/L

### 3.4 TECHNICAL MITIGATION OPTIONS

Brine discharge systems need to be designed to minimize environmental impacts while being in compliance with regulatory demands. A major principle before working on the brine discharge designs is to reduce the source concentrations and loads by proper mitigation measures within the desalination plant (e.g., reducing additive usage and dosing, improving plant efficiency, etc.), or proper intake and pre-treatment technologies. The design of brine discharge area involves the application of enhanced mixing technologies like multiport diffusers, sited in less sensitive regions; i.e., offshore, deep waters [12]. Brine discharge system of SPWS is a single port onshore submerged structure. The existing brine discharge structure has achieved the Mixing Zone Water Quality Standards set by the Government of Bahrain, but still mitigation scenarios aimed at improving the initial mixing before interacting with boundaries and reducing the distance of total mixing (i.e., equal to ambient) need to be explored and investigated. This can be met by offshore submerged multiport diffusers and offshore submerged single port diffusers. However, these two mitigation scenarios are not applicable to existing old desalination plant, and can be applied for new desalination plant.

### 3.4.1 MIXING COOLING WATER WITH BRINE DISCHARGE

One of the technical mitigation solutions that can be implemented is to mix the cooling water from the power side, which have temperatures almost equal the ambient, with the discharged brine. This mitigation will be beneficial and could have a significant effect, especially in winter season when the difference between the discharged brine temperatures and the ambient seawater temperature is high and reaches 20°C.

The cooling water from the power plant is rejected to the outfall with the same ambient TDS but with higher temperature than the ambient by 5 °C. The CORMIX discharge calculator is used to compute the final effluent characteristics including the effluent from power plant during the winter season [13]. The final outfall temperature after mixing the two waters is 34.68 °C, its TDS at 48,390 mg/L, and a total flow of 15.5 m3/sec. Table (7) shows the input data and the results of the simulation.

Table 7: Flow rates input data and simulated effluent characteristics for SPWS (MSF) plant

| **Ambient Characteristics (=intake water)** | |
|---|---|
| Ambient temperature | 20.0 °C |
| Ambient salinity | 40.0 ppt |
| Ambient density | 1028.30 kg/m$^3$ |
| Ambient kin. viscosity | 1.06E-06 m$^2$/s |
| **Fresh Water (desalinated)** | |
| Flow rate | 1.10 m$^2$/s |
| Recovery rate | 30% |
| Distillation intake flow rate | 3.67 m$^3$/s |
| **Brine Characteristics (effluent from desalination process)** | |
| Brine flow rate | 10.0 m$^3$/s |
| Temperature | 40.0 °C |
| Salinity | 53.0 ppt |
| Density | 1031.07 kg/m$^3$ |
| **Blended effluent (external)** | |
| Flow rate | 5.50 m$^3$/s |
| Temperature | 25.0 °C |
| Salinity | 40.0 ppt |
| Density | 1026.79 kg/m$^3$ |
| **Desalination plant characteristics (without cogenerating power plant)** | |
| Feed water flow rate | 3.67 m$^3$/s |
| Rejected effluent flow rate | 10.0 m$^3$/s |
| Recovery rate (desalination plant) | 30% |
| Effluent temperature | 40.0 °C |
| Temperature difference to ambient | 20.0 °C |
| **Final Effluent Characteristics (including effluent from cogenerating power plant)** | |
| Flow rate | 15.50 m$^3$/s |
| Effluent temperature | 34.68 °C |
| Temperature difference to ambient | 14.68 °C |
| Effluent salinity | 48.39 ppt |
| Effluent density | 1029.71 kg/m$^3$ |
| Buoyant acceleration | -0.01344 m/s$^2$ |

Under this mitigation option, the NFR will drop from 0.56 m to 0.39 m and the cumulative travel time to the end of NFR decreases from 54 sec to 35 sec. The temperature at the edge of NFR is equal to the effluent temperature (14.68°C), where the temperature before mitigation was 20 °C above the ambient temperature. The results predicted at the NFR boundary are summarized in Table (8).

Table 8: NFR characteristics

| | |
|---|---|
| Temperature at the edge of NFR | 14.68 °C above ambient |
| Dilution at the edge of NFR | 1 |
| NFR location | X: 0.39 m, Y: 76.74 m, Z: 2.68 m |
| NFR dimension | Half width: 1.79 m, Thickness: 2.68 m |
| Cumulative travel time | 34.99 sec |

The temperature at the edge of the RMZ (i.e., 100 m from the plant reject point) drops from 0.5 °C above the ambient to 0.3 °C. The results show that in approximately 22.5 minutes the plume elevated temperature drops down to equal the ambient temperature while covering a distance of 190 m downstream, whereas before this mitigation option the elevated temperature drops down to the ambient temperature after covering 350 m in 37 minutes. The comparison in temperature drop before and after this mitigation option is illustrated in Figure (10).

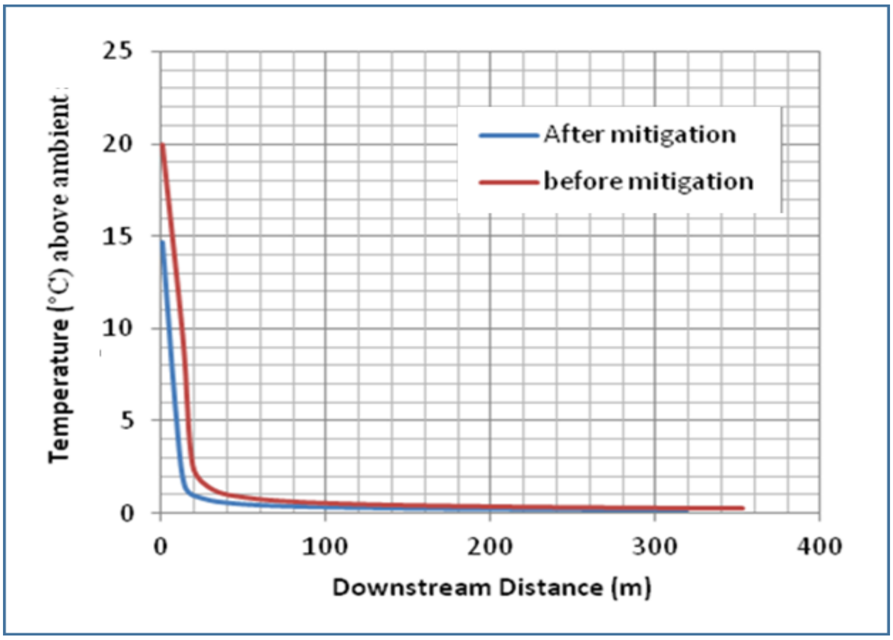

Figure 10. Comparison in temperature drop before and after mitigation

The characteristics of the final effluent resulting from mixing cooling water from the power side with the discharged brine lead to a drop in the TDS from 53,000 mg/L to 48,000 mg/L. The concentrated brine discharge takes about 17 minutes to dilute the concentration from 8,000 mg/L above the ambient TDS to 172 mg/L above the ambient level at the end of RMZ as shown in Table (9).

Table 9: RMZ characteristics

| | |
|---|---|
| TDS at the edge of RMZ | 172 mg/L above ambient |
| Dilution at the edge of RMZ | 46.3 |
| RMZ location | X: 100 m |
| RMZ dimension | Half width: 11.51 m, Thickness: 6.47 m |
| Cumulative travel time | 1032.13 sec |

Before mitigation the TDS at the edge of RMZ was 240 mg/L above the ambient TDS. The results also showed that in approximately 22 minutes the plume elevated TDS drops to the ambient TDS, while covering a distance of 200 m downstream, in comparison to the current conditions where the plume's elevated TDS drop to the ambient TDS within 41 minutes and covering a distance of 400 m along the downstream.

## 4. CONCLUSION AND RECOMMENDATIONS

The assessment of the environmental impact of seawater desalination at the outfall area of a government-owned MSF desalination plant (SPWS) indicated that the temperature of the brine discharge from the plant is within Bahrain Mixing Zone standards during the winter season. However, the difference in temperatures between the discharged brine and the ambient is relatively high reaching 20°C. The simulated temperatures at the outfall area showed that the plume elevated temperature drops down to almost the ambient temperatures in approximately 37 minutes after traveling a distance of 350 meters downstream. The plume elevated salinity drops to the ambient seawater salinity after approximately 41 minutes after traveling a distance of about 390 meters downstream.

A technical mitigation option represented by mixing of power cooling water with brine is investigated for the winter season using the developed simulation model and have shown a high potential for mitigation. The results showed that this mitigation option has the potential of reducing the impacts of temperature by 30% and that of the salinity by 38%. Under this mitigation option, the plume elevated temperature drops down to almost equal to the ambient temperature in a distance of 190 m downstream in approximately 22.5 minutes, while the plume elevated salinity drops to the ambient salinity in a distance of 200 meters in 22 minutes.

It is recommended that a regular monitoring program of the seawater quality at the outfall area of the desalination plant, namely the Near Field Region (NFR) and the Regulatory Mixing Zone (RMZ), is designed and implemented to aid in a better monitoring, characterization, and simulation of the outfall region. Such regular monitoring program should include other quantifiable environmental indicators, such as brine chemicals and biological communities. Moreover, while this research has focused on the outfall impact on the marine environment in terms of brine temperature and salinity, it is recommended that greenhouse gases emissions be included in the environmental assessment of the impacts of desalination plants.

A similar characterization and environmental impact assessment is recommended to be carried out on the outfall areas of the other desalination plants in Bahrain, which use other technologies (MED and RO) and are located at different hydrodynamic sittings of the marine environment, and of which the majority are owned by the private sector. In addition to characterizing and assessment of the environmental impacts of these plants, such studies could help the municipal water authorities in their future technology selection from an environmental perspective.

## 5. REFERENCES

1. Al-Zubari, W. K., (2014). The Costs of Municipal Water Supply in Bahrain. Energy, Environment and Resources (Produced as part of the Valuing Vital Resources in the Gulf series), Chatham House, UK. Available at: http://www.chathamhouse.org/sites/files/chathamhouse/field/field_document/20141216MunicipalWaterBahrainAlZubari.pdf.
2. Bleninger, T. and Jirka, H. (2008). Modelling and environmentally sound management of brine discharges from desalination plants. Desalination, 221: 585–597.
3. Alameddine, I. and El-Fadel, M. (2007) Brine discharge from desalination plants: a modeling approach to an optimized outfall design. Desalination 214: 241-260. Doi:10.1016/j.desal.2006.02.103.
4. Abualtayef, M., Al-Najjar, H., Mogheir, Y. and Seif, A.K. (2016) Numerical modeling of brine disposal from Gaza central seawater desalination plant. Arabian Journal of Geosciences 9:572. Doi:10.1007/s12517-016-2591-7.
5. Altayaran, A. and Madany, I. (1992). Impact of a desalination plant on the physical and chemical properties of seawater. Bahrain. Water Research 26 (4), 435-441. Available at: http://www.researchgate.net/publication/248328202_Impact_of_a_desalination_plant_on_the_physical_and_chemical_properties_of_seawater_Bahrain.
6. Doneker, R.L. and Jirka, G.H. (2007). User's manual for CORMIX: A hydrodynamic mixing mixing zone model and decision support system for pollutant discharges into surface waters. U.S. Environmental Protection Agency.
7. Anderson, M.P. and Woessner, W.W. (1992). Applied groundwater modelling simulation of flow and advective transport. University Press, Cambridge, 296 pp.
8. El-Sadek, A. and Vazquez, R. (2012). Parameter sensitivity analysis and prediction error in field-scale NO3-N modeling. Agricultural Water Management, 111: 115-126.

9. Ducheyne, S. (2000). Derivation of the parameters of the WAVE model using a deterministic and a stochastic approach. PhD thesis No. 434, Faculty of Agriculture and Applied Biological Sciences, K. U. Leuven, Belgium, 123 pp.
10. Mixing Zone Water Quality Standards. (2001). General authority for the Protection of Marine Resources, Environment and Wildlife (currently Supreme Council for Environment), Kingdom of Bahrain.
11. PCPMREW (Public Commission for the Protection of Marine Resources, Environment and Wildlife) (2012). Bahrain's Second National Communication under the United Nations Framework Convention on Climate Change (UNFCCC). Kingdom of Bahrain.
12. Bleninger, T., Lattemann, S., Purnama, A., Al-Barwani, H.H., Doneker, R.L., Jirka, G.H.,. (2009). Brine Dis-Environmental planning, prediction, and management of Brine Discharge from seawater desalination plants. Arab Water World (AWW) magazine, Vol. XXXIII issue No. 4, April 2009.
13. El-Dessouky, H. and Ettouny, H., (2002). Fundamentals of Sea Water Desalination. Elsevier Science B.V. 670p.
14. Shahin, M., Van Oorschot H.J.L. and De Lange, S.J. (1993). Statistical Analysis in Water Resources Engineering. A. A. Balkema Publishers, The Netherlands. 394 pp.
15. Legates, D.R. and McCabe G.J. (1999). Evaluating the use of 'goodness-of-fit' measures in hydrological and hydroclimatic model validation. Water Resources Research, 35 (1): 233-241.

# ANNEX A
# STATISTICAL CRITERIA FOR THE EVALUATION OF MODELS PERFORMANCE

## *1. RELATIVE ROOT MEAN SQUARE ERROR (RRMSE)*

$$RRMSE = \frac{\sqrt{\frac{1}{n}\sum_{i=1}^{n}(P_i - O_i)^2}}{\bar{O}} \qquad (1)$$

where $\bar{O}$ is the mean of the observed values over the time period (1 to n). The RRMSE has a minimum value of 0.0, with a better agreement close to 0.0.

## *2. GOODNESS OF FIT (R2)*

$$R^2 = \left[\frac{\sum_{i=1}^{n}(O_i - \bar{O})(P_i - \bar{P})}{\sqrt{\sum_{i=1}^{n}(O_i - \bar{O})^2}\sqrt{\sum_{i=1}^{n}(P_i - \bar{P})^2}}\right]^2 \qquad (2)$$

where $\bar{P}$ is the mean of the predicted values over the time period (1 to n). $R^2$ is ranging from 0.0 to 1.0 indicating a better agreement for values close to 1.0 and it is known as the goodness of fit [14][15]. The characteristics of the different statistical criteria are given in Table 10

Table 10. The characteristic of the different statistical criteria

| | |
|---|---|
| Relative Root Mean Square Error (RRMSE) | |
| RRMSE=0 | model is perfect |
| RRMSE=min | model is optimal |
| Goodness of Fit ($R^2$) | |
| $R^2$=1 | model is perfect |
| $R^2$=max | model is optimal |
| $R^2$=0 | model has no prediction capability |