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Modelling potential drivers of fish kill events in Sulaibikhat Bay, Kuwait

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Abstract—**The marine environment of Kuwait Bay, a shallow, tidally dominated area at the margin of the northern and westernmost extreme of the Gulf of Arabia is one of the harshest on the planet. Air temperatures have been known to reach 52 °C, with water temperatures above 30 °C in the summer months. Stratification and mixing in the shallow bay is influenced by freshwater input of the Shaat-al-Arab waterway to the east, by exceptionally high rates of evaporation, and mixing driven by the periodic "Shamal" winds, blowing over the Bay from the north west.**

Coupled with the harsh physical conditions, are the impacts from discharging domestic and industrial waste pollutants and thermal or hypersaline plumes from industrial plants into the Bay, which severely impact marine biota.

In recent years, several catastrophic "fish-kill" events have occurred when physical and anthropogenic conditions have contrived to demonstrate the frailty of the marine system. The most recent of these, in Sulaibikhat Bay, an embayment at the western end of Kuwait Bay, occurred in April 2017 and demonstrated further fragility in the local marine system.

The UK's Centre for Environment, Fisheries and Aquaculture Science (Cefas) developed a Telemac-2D tidal model of Kuwait Waters, coupled with the Telemac integrated water quality module (WAQTEL) to simulate the conditions which may cause such lethal events. Whilst a full water quality modelling process of the region relies on comprehensive knowledge of initial conditions, the modular application of Telemac-2D with the O_2 modules of WAQTEL re-create the likely conditions in Sulaibikhat Bay when the fish kill events occur. We demonstrate how the potential build-up of pollutants coupled with high temperature, salinity and poor flushing of the Bay, partly due to the wide diurnal inequality experienced at the site, reduce levels of dissolved oxygen close to and in places exceed critical thresholds at times. Whilst some species have greater tolerance to these events, other populations are devastated when exposed to such conditions for any length of time. The management and eradication of these events can be effected when they can be accurately simulated and the hazards closely defined.

Introduction

The coastal zone of Kuwait, in keeping with many of its Gulf neighbours has a densely populated and developed coastal zone where residential and industrial land-use exist close to one another. The southern coastline of Kuwait Bay, where Kuwait City has expanded inland and southwards along sandy eastern coastline over the last 5 decades, represent the modern city today and increasing stress is placed upon the marine domain from many quarters. Anthropogenic activities, creating discharges of pollutants which impact the marine biota, have increased significantly during this time and the design and management of procedures to monitor and maintain high water and sediment quality systems need to be considered with great care to ensure the effects of discharges are mitigated [4].

Kuwait Bay is situated at the north-western tip of the Arabian Gulf. It is characterised by a semi-enclosed shallow body of water, about 35 km wide with a mean depth of 5 m, a strong semi-diurnal tidal regime and a maximum depth of about 20 m, covering an area about 750 km^2 [5].

Physical and environmental conditions causing sporadic loss of marine biota have occurred with increasing regularity; in 2001 an estimated 3000 tonnes of fish were killed during the hot August and September period, and as recently as April this year when less severe, but similar fish-kill occurred generating some condemnation of marine management systems and the environmental authorities in the local media [3].

Objectives

Kuwait's extreme marine conditions, particularly in the embayment of Sulaibikhat Bay, are brought about by several physical phenomena which combine to maximise their impact at certain times of the year. Air temperatures around 50 °C; high rates of evaporation contributing to high salinity; low rates of precipitation and limited freshwater input; wind driven mixing, are the natural drivers which contribute to reducing the capacity of the water column to hold oxygen. There are several anthropogenic influences, including industrial scale and domestic waste outfalls distributed along the Kuwait City frontage, contributing to the chemical and biological oxygen demand. Numerous outfalls from power station cooling waters, de-salination plants, refineries and major industrial plants also contribute to the degradation of water quality on the coastal zone.
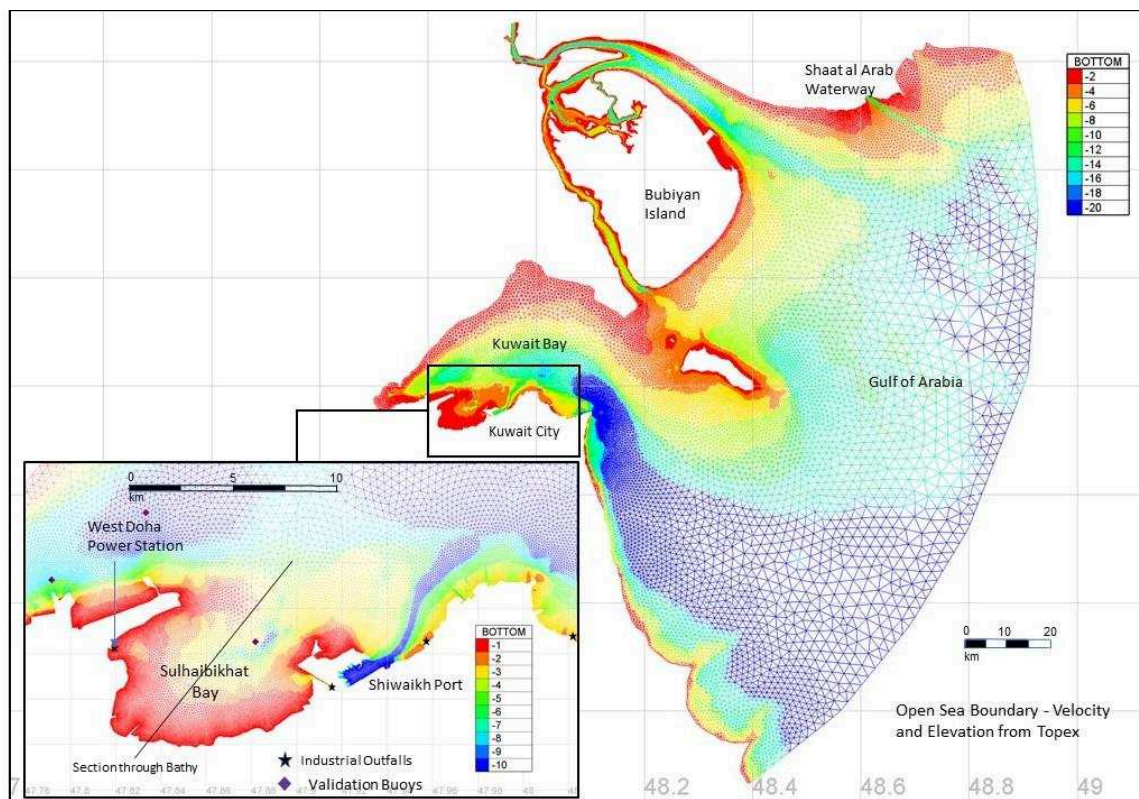
Figure 1. *Telemac2D regional model of Kuwaiti Waters and inset showing the detailed model area of Sulaibikhat Bay; the outfalls at Al Ghazali, Al Bida'a either side of the Port, and Power Station outfalls are shown in relation to the Bay.*

Water temperatures in Kuwait Bay range from an average value of 15.5 ºC in February to a high of 32.3 ºC in August. These values, coupled with high salinity driven by high evaporation and reducing fresh water inputs from the Shaat-al-Arab, reduce the saturation value for dissolved oxygen in the water column even further.

The objective of this study was to create a depth averaged hydrodynamic solution (adequate in the shallow, well mixed zone under investigation), to demonstrate the factors which combine to inhibit circulation and physical attributes which reduce and deplete dissolved oxygen in the embayment at times when physical stressors are at a maximum. However, the amount and quality of data available to validate inputs and outputs of various components in the model is sparse and the results obtained from the present study are only considered qualitative. They do however suggest that during the periods when these conditions align, dissolved oxygen values in the water column are likely to be below the value needed to support fish species.

TELEMAC-2D MODEL – KUWAIT WATERS

A   Model Setup

The Telemac-2D model developed for this study covers the area of Kuwaiti National Waters, at just over 12,000 km² and is driven by tidal harmonics derived from satellite sensed sea-surface elevations, at its open sea boundary. Whilst 3D models have been successfully applied to demonstrate the importance of the freshwater inputs at Shaat-al-Arab

waterway for altering circulation and residence times in the Northwest Gulf [1], for this study a Telemac-2D model was considered suitable. The principal area of interest, Sulaibikhat Bay, at the western end of Kuwait Bay is a shallow embayment (mostly <5m depth) bounded by tidal flats to the west and south and the industrial development of Shuwaikh Port to the east. On its western shore, the cooling water outfalls of Doha Power Station release a hot water plume of approximately 50 m³s⁻¹ and flows into the embayment. The plume exhausts from the cooling function of the power station release water with a relative temperature elevation estimated to be 11ºC higher than the intake water temperature.

The model mesh uses bathymetry synthesized from the General Bathymetric Chart of the Oceans (GEBCO) (30 sec), UK Hydrographic Office and augmented by the author's single beam surveys made in 2014 during the Mishref Study [5]. The model is relatively simple in operation employing constant viscosity and options for tidal flats which ensure the large drying regions are included in this tidally dominated region of the Gulf. Details of the Telemac2D model mesh are shown in Fig. 1.

The model resolution increases to a density of 50m along the shoreline of Sulaibikhat Bay and the developed frontage of Kuwait City where the six major releases of treated effluent and industrial waste into the Bay occur.
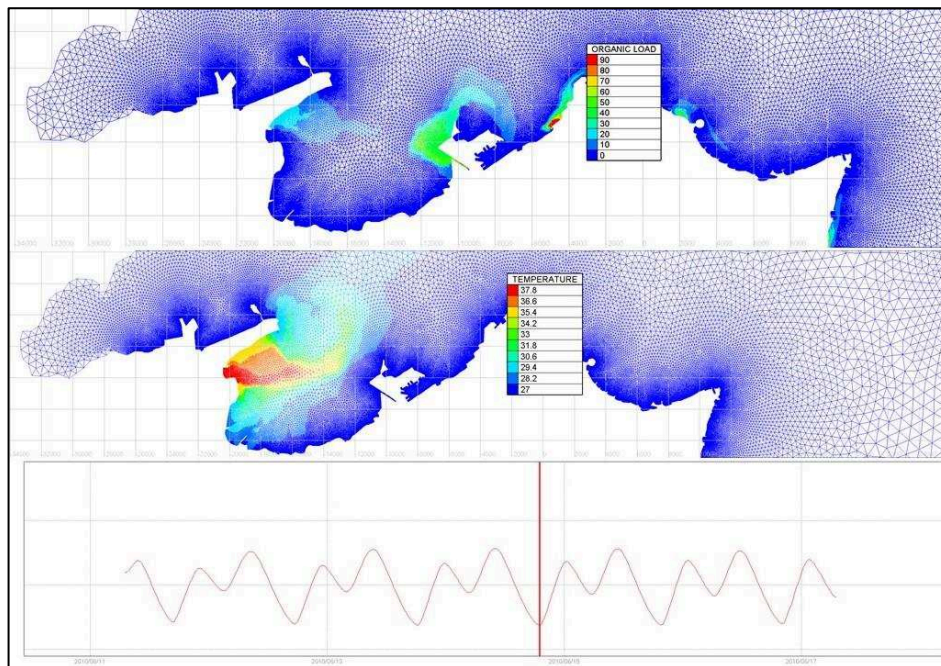
Figure 2. *Organic load from Al Ghazahli outfall and heated water from the power station trapped against the coast at a low spring tide.*

B Local Conditions

The embayment at Sulaibikhat provides a challenging environment for marine animals. At this end of Kuwait Bay, a tidally dominant coastline exists, with a spring range of ~3.2m and neap range reducing to ~1.5m. The embayment itself is shallow (maximum depth of ~4m) and a submarine sill exists across the mouth of the embayment. During each intermediate tide, high diurnal inequality in the local tidal regime severely inhibits flushing of the embayment and as a low spring tide coincides with the top of the sill then flushing is prevented or partially inhibited during each tide. The combination of high sill level and tidal regime can entrap potentially harmful pollutants and waste in the embayment.

The sill also traps heated water from the Doha Power station, released at the extreme west end of the Bay, such that heat cannot dissipate freely. The effect of the hot water is detrimental to dissolved oxygen saturation in the embayment and some elevation of temperature exists until the bay can be flushed on the next tide. These effects are shown in Fig. 2 where pollutants and heated water are trapped and lie close to the coast.

C Validation

Validation data for hydrodynamic models are difficult to obtain locally. However, time series of observations provided by the Kuwait Meteorology Department provided enough data to calibrate and validate the Telemac-2D model against elevations and velocities. The Kuwait Environment Public Authority is currently working to develop the Environmental Monitoring Information System of Kuwait (eMisk), a modern GIS based, information system. One aspect of this is for the marine region and in time, as this becomes more fully operational a fully integrated marine monitoring and regulatory process will be at its core and will provide calibrated ocean management, monitoring and modelling systems.

For this study the model's performance was evaluated using the method of [8] (Relative Mean Absolute Error – RMAE). The final parameters used for the Telemac2D hydrodynamics used a Nikuradse friction method with $K_s=0.05$; Kinematic Viscosity=10^{-4} ; Amplitude Coefficient = 1.1;. These values achieve a RMAE of 0.25 for Elevation and 0.29 for Velocity.

D Waste Inputs – Sources and Tracers

The six waste outfalls which serve the sewerage treatment plants in Kuwait, processing waste from 3.6 million inhabitants of Kuwait's metropolitan area, have been beset with reliability issues for periods of time during recent decades. Much work has been carried out to upgrade the system but at times up to 150,000 m³ of raw, untreated waste has been released into the Kuwait coastal zone, in this instance from the Mishref pumping station breakdown in 2009 [5], [7].

Precise measurements of the outfall discharges and concentrations of tracers are not available at present and assessments of likely values have been made by colleagues at site. The total discharge at each outfall was assessed to be 60% of the output during the periods when unprocessed material was released (1.736 m³s⁻¹). Tab. 1 shows the concentrations used at the sources in the model and the tracer inputs to the WAQTEL module.

The O_2 module of WAQTEL will trace sources of Organic Load (Biological Oxygen Demand), Ammoniacal Load (Ammonium NH_4) and Dissolved Oxygen. Background

values for these source inputs were set as 3 mgl⁻¹ and 0.01 mgl⁻¹ each. For environmental conditions prevailing in Kuwait Bay, water temperature at a mean value of 28 °C and salinity of 40 ppt, a background value for dissolved oxygen of 6 mgl⁻¹ was used. A comprehensive study in 2008 [2], reported a slightly lower average value in Kuwait bay for dissolved oxygen of 5.3 mgl⁻¹ however gradients exist between conditions nearer to Bubiyan Island and less developed coasts on the north of the Bay where wide expanses of shallow tidal flats act to reduce the average.

E Water Quality – WAQTEL

Water Quality Processes are invoked in the Telemac-2D code with a call to WAQTEL, controlled by a separate steering file. The O_2 module of the WAQTEL system is used to compute the density of dissolved oxygen in the water. The methodology is designed to be simple [9] and computes the

residual quantity of an O_2 tracer based on relatively simple methods to evaluate sources and sinks which control the evolution of O_2 in the water column. It does not consider the full complexity of biological interaction and uses co-inputs of Organic Load (BOD) and Ammoniacal Load (NH_4), the elements which represent typical treated waste from sewage treatment plants.

The residual dissolved oxygen value is computed by reconciling the following sources and sinks for O_2:

$$F([O_2]) = K_2(C_s-[O_2])-K_1[L]-K_4[NH_4]+P-R-\frac{ben}{h} \quad (1)$$

Where: C_s = O_2 Saturation density of water; K_1 =Constant of Degradation of Organic Load (L) ; K_2 =Reaeration Coefficient; K_4 = Constant of Nitrification; P = Photosynthesis; R = Vegetal Respiration; ben = Benthic Demand; h=depth of water.

The separate components of (1) should be calibrated and several options are available to effect this within the steering files or directly within the calc_o2.f source code. Without alteration, the simplistic method of summation of values can result in negative values for O_2 concentration.

In Kuwait, the harsh physical conditions affect some of these components such that the default values are not valid and need to be adjusted.

The default values of K1, Constant of degradation of Organic Load and K4, Constant of Nitrification were used in the model. Values of 0.25 and 0.35 degrade the tracers in time and are independent of other factors.

K2, the coefficient of Re-aeration, offers options for method of computation. Firstly, a variety of empirically derived parameterisations can be selected to determine a value. These are strongly dependent upon flow velocity and depth, but valid for a water temperature of 20 °C. Therefore, a second adjustment is made to consider the high-water temperature in the Bay (average value of 28 °C in June). This adjustment increases the re-aeration coefficient by a factor of 20%, in the mostly shallow conditions with moderate tidal

strength in the Bay, re-aeration is likely to be stronger than that set by default.

Values for Photosynthesis and Vegetal Respiration, which are a source and a sink of oxygen respectively, were kept at default values. Both values are relatively low in the Kuwait conditions. Poor water clarity degrades light availability although shallow conditions in the embayment are likely to boost photosynthesis. There is sparse vegetal growth on the tidal sand flats and in the embayment and related respiration is likely to be at a minimum.

Benthic Demand, also dependent upon water depth, is evaluated at 20 °C and an increased coefficient is used which for a temperature of 28 °C, enhances demand by up to 65%.

RESULTS

A Deployments

In each case in this section where point values are presented they are considered at a point coincident with the location of a smartbouy deployment made by the Environment Protection Authority of Kuwait and located at the centre of the Sulaibikhat Bay, the location indicated on Fig.1. The location is in the deepest part of the embayment before the sill rises to create shallow conditions again. Whilst this deployment forms one of twelve new monitoring stations incorporated into the eMisk programme it is not yet fully operational. Sensors for dissolved oxygen and CTD have not yet been calibrated in-situ and data are not yet telemetered.

B Hydrodynamics

The model was run for a relatively brief period (6 days) given the caveats for the operation of the O_2 module, of it being valid for a period of several days only. The hydrodynamics were validated for a month-long period and validation statistics showed that in its 2D form, the Telemac hydrodynamic performance is good to excellent [4].

TABLE 1. TRACER LOCATIONS AND INPUTS TO THE MODEL

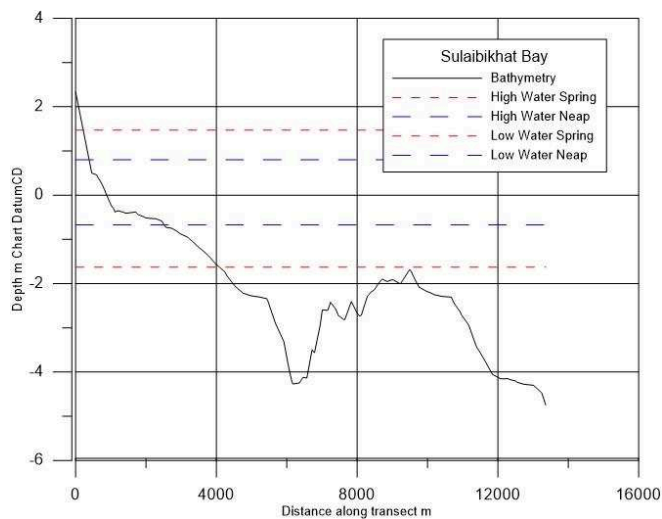| Name	Lat	Lon	Q	O₂	Org. Load	NH₄	Temp
			m^3s^{-1}	mgl^{-1}	mgl^{-1}	mgl^{-1}	$°C$
Al Ghazali	29.34	47.90	1.0	6.0	125	125	28
Al Bida'a	29.32	48.09	1.0	6.0	125	125	28
Al Khitabi	29.30	48.08	1.0	6.0	125	125	28
Al Messela	29.27	48.09	1.0	6.0	125	125	28
Chin. Rest.	29.36	48.02	1.0	6.0	125	125	28
Sher. Hot.	29.36	47.95	1.0	6.0	125	125	28
Pwr Stat. o/fall	29.36	47.81	50.0	0	0	0	39

Figure 3. *Relationship between the embayment bathymetry and Spring, Neap High and Low water levels.*

C   Dissolved Oxygen Concentration

The impact of natural diurnal inequality is a dominant factor inhibiting polluted water from flushing out of the embayment. Fig. 3 shows the relationship between HW and LW Spring and Neap tidal conditions and their absolute levels in relation to a transect along the seabed for 13.5km from shoreline of Sulaibikhat Bay out into Kuwait Bay (shown in Fig.1). Whilst over 50% of the area of the embayment dries to tidal flats on low water of a spring tide, the sill prevents exchange of water at tidal levels above this also.

Whilst temperature was added as a tracer in the discharge from the power station outfall it was not included in the computations of the model for this study. The model was run in a barotropic mode, without the effect of salinity, and the final evaluation of dissolved oxygen, which includes the effect of salt on dissolved oxygen concentration, was post-processed. A factor of 80% was applied to the computed values of dissolved oxygen to allow for a salinity of up to 40ppt and temperature of 28°C [3].

The effect of temperature on the dissolved oxygen concentration is linear in this model and to improve the results, temperature should be included as a direct variable in the O2_calc.f subroutine. However, the elevated temperatures in this model were applied in the WAQTEL module and the hot water plume effect reduces dissolved oxygen values by up to 0.87 mgl^{-1} with these at their maximum at low water when flushing is prevented.

Absolute values of dissolved oxygen measured by the Kuwait EPA buoy deployment in the centre of the embayment reduce to levels of 4.89 mgl^{-1} at low water of a spring tide. During the low neap tide condition, this degrades further to a value of 4.28 mgl^{-1}.

Fig. 4 shows the value of dissolved oxygen across the embayment at a low Neap tide, values close to the source outfalls at negligible levels but in the centre of the embayment the extent of the lowered values ~4.2 mgl-^{1} is clear.

DISCUSSION

The objective of the study was to highlight factors which combine under certain conditions to inhibit circulation and flushing and degrade dissolved oxygen levels when pollution and elevated water temperatures are trapped in Sulaibikhat Bay. This occurs for particular durations of the tidal cycle, and for much of the time the model does not show reductions in the level of dissolved oxygen of such severity to cause the rates of mortality in fish species observed in recent years.

Whilst the power station (in this case) and other industrial plants add plumes of hot or hyper saline water to the marine environment of the embayment, the discharge of the plumes act to invoke strong re-aeration due to turbulence generated in the outfall. The design of this structure takes the form of a spillway and mixing, dissipation and re-aeration are strong in this case. The model simulates this by the relative dimensions of the discharge boundary and strength of the discharge rate applied.

The embayment is generally sheltered, its location at the extreme southwest of Kuwait Bay means that the prevailing "Shamal" winds from the northwest determine that wave activity in the area is relatively low. Waves would act to reaerate the water column strongly but the surface conditions of the embayment are calm for much of the time.

The embayment has a mostly natural shoreline formed of tidal sand flats and few structures exist to add turbulence to the flow. However, the new development of the Sheikh Jaber Al Ahmed Causeway will add a line of twin ~5m diameter support columns, at approximately 25m centres. The structure will cross the entire 10 km long mouth of the embayment. The bridge will then continue to the northeast, extending across Kuwait Bay to the new Silk City Development on the northern coast of the Bay. One effect of the substructures of this construction will be to generate further turbulence from the mesa-tidal flows which can also act to improve re-aeration.

The rates of mortality observed in the fish-kill events which have occurred in the embayment, are not likely have been driven solely by catastrophic reductions in the levels of dissolved oxygen. A combination of several factors should be attributed.

The levels of pollution emitted in the area, whilst fixed in the model are likely to change significantly over the period of a day and recorded events such as the Mishref crisis [4] indicate that at times, the failure of treatment plants and emergency measures invoked to prevent build-up of untreated waste at these times, can result in the release of much higher concentrations of organic and ammoniacal load than used in this simulation.
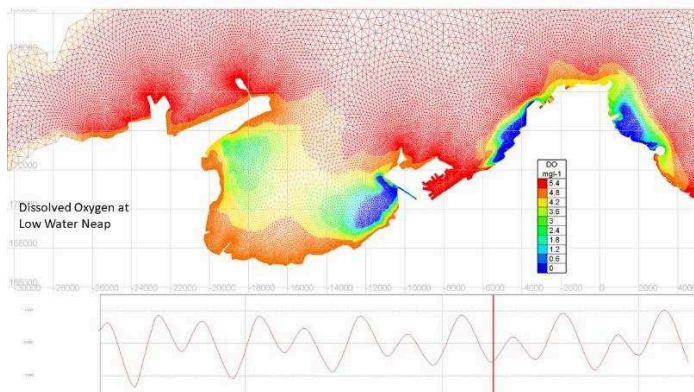
Figure 4. *Absolute values of dissolved oxygen computed at Neap low water, the condition at which values are at their minimum in the embayment where the fish kill events have occurred.*

The range of minimum dissolved oxygen concentrations for cold water and warm water fish species is wide; warm water fish are generally more tolerant to lower oxygen levels, reflected in Water Quality Standards around the world. For salt water fish in the warm and salty water conditions of this embayment, tolerance to lower oxygen levels is likely to be high. Levels of 7-5 mgl[1] are considered normal whilst levels which drop to 4 mgl[-1] will generate stress in some species and fatalities at oxygen levels at 50% of this [5].

The model demonstrates that these conditions could certainly exist at times when the stressors of oxygen depletion coincide.

When the fully developed eMisk marine monitoring system is implemented much higher quality and validated datasets will be available to calibrate these type of model simulations.

CONCLUSIONS

The study provided an opportunity to implement a trial of the Telemc2D-WAQTEL, O_2 module although its application in this setting is complex and presents challenges in attaining the correct values for the calibrating coefficients which ultimately control the computation of dissolved oxygen.

The work demonstrates the fragility of the marine system to maintain safe levels of dissolved oxygen in the environment of Sulaibikhat Bay, at the west end of Kuwait Bay. Whilst these were not proven to be at fatal levels during the short periods simulated, the elements which control dissolved oxygen levels in the model are those which can inform the causal effects of harmful low levels in the environment.

ACKNOWLEDGEMENTS

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