Variable Wind Speed and Evaporation Rates: A Practical and Modelling Exercise for High School Physics and Multi-Strand Science Classes

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ABSTRACT

With the recent onset of drought conditions throughout many regions of Australia and across the world, a greater amount of interest has been placed on the measurement and modelling of evaporation rates in real-world environments such as agricultural dams and drinking water reserves. Coinciding with this, substantial amounts of research work have been carried out detailing increasingly accurate methods to both measure and predict evaporative losses from water reserves along with the development of innovative techniques and technologies to suppress and mitigate water evaporation. Some examples of these techniques include fixed covers, floating covers, wind breaks along with chemical films and monolayers. The following practical exercise aims to give senior high school Physics and multi-strand science students an insight into how evaporation measurements can be made and compared with modelled data to verify their accuracy by employing local wind velocity, temperature (air and water) and water vapour (humidity) information. In addition to this, this exercise shows how publicly available chemical films based on substances such as silicon, cetyl alcohol and stearyl alcohol can be utilised to reduce evaporation. An analysis of film performance under varying wind velocities will be detailed for replication by students in the laboratory.

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INTRODUCTION

The objective of this practical exercise is to run a series of experiments to record both baseline and wind enhanced evaporation measurements within a self-contained indoors water basin (water tank) and to compare these real-world physical measurements to modelled data obtained from an evaporation equation. These measured and modelled results will then be evaluated against a further series of baseline and wind enhanced evaporation measurements with several types of evaporation reducing chemical films or monolayers present on top of the water surface. From this work students can gain an understanding of how mathematical models can be used to validate real-world measurements and how chemical films and monolayers can be employed to reduce water losses caused by variable atmospheric conditions such as increases in wind and temperature. The teacher can easily demonstrate the basic principles and methodologies to the students in the space of a single 45 minute to 1 hour class. The students can then perform the practical work over the space of another 45 minute to 1 hour class or over a longer period of time as determined by the teacher.

Drought coupled with excess water wastage has been a serious issue facing both the Australian and global population. Even after the substantial rainfall that has fallen across eastern Australia in recent months, it is critical that our newly supplemented water reserves be protected from future drought periods. As a result, many different systems have been developed to reduce water loss. Some of these include hard and floating water surface covers, shade sails, wind breaks and destratification mechanisms. Unfortunately, many of these advanced large scale evaporation mitigation solutions can be expensive and difficult to install and maintain, pose a threat to the health of local environments and ecosystems and can severely reduce the aesthetic appeal and restrict the public recreational use of a water reserve. However, environmentally friendly, cost-effective and easily deployed chemical films and monolayers that sit on top of the water surface have been developed and used over the last fifty years by agricultural, commercial and government end users.

A chemical monolayer is a long chain molecule that features one hydrophilic end and one hydrophobic end similar to a typical soap molecule studied in high school chemistry courses. This configuration allows the monolayer to quickly spread out and sit on top of a body of water in a closely packed regime usually only a few nanometres thick effectively trapping the escaping water vapour beneath it. Unfortunately, monolayers are very susceptible to wind and wave action which causes them to stretch and scatter on the water surface. Monolayers and chemical films can also be removed from the water surface by escaping water molecules. Most types of chemical film/monolayer can only last for about two days on dams in typical Australian conditions before requiring reapplication (Craig *et al*, 2007). Two examples of commonly used and readily available chemical films and monolayers are discussed in the following paragraphs. Due to their availability and extremely low biological/environmental risk, these two chemical films/monolayers can be used in the classroom experiments detailed in this article.

WaterSavr (www.phoslock.com.au/watersavr.php) is a commercially available chemical monolayer product that has been used to a large extent in the Australian agricultural industry. WaterSavr is comprised of s calcium hydroxide (lime), cetyl alcohol (commonly referred to as hexadecanol) and stearyl alcohol (commonly referred to as octadecanol). Figure 1 (A) shows a sample of WaterSavr in its dry form before application and Figure 1 (B) depicts the spread and distribution of WaterSavr over a small water surface area. Note how the WaterSavr particulates have a tendency to cluster together around the edges of the container.

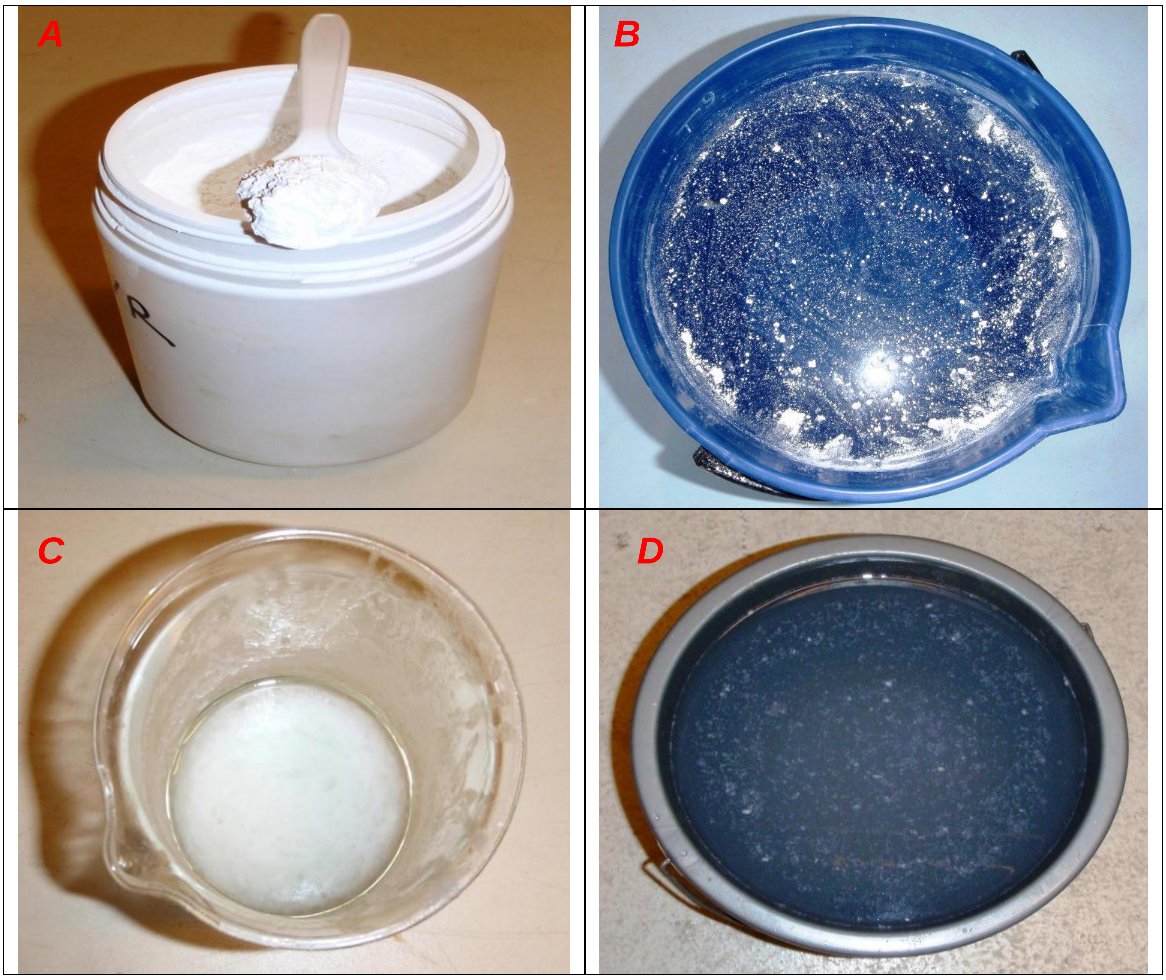

Figure 1 – A) WaterSavr chemical film in dry form before application. B) WaterSavr chemical film spread out across a small water surface area. C) Aquatain chemical film before application. D) Aquatain deployed over a small water surface area.

A new chemical film product called Aquatain (www.aquatain.com.au) has been recently released to the public. Aquatain uses a silicone base that makes it less sensitive to the environmental stress factors, such as wind and wave action, that have plagued the use of the cetyl alcohol and stearyl alcohol based monolayers and can also be safely used on top of drinking water supplies. It is not regarded as a conventional monolayer as its typical spreading thickness is much greater than a few nanometres. Additionally, it is believed that Aquatain causes no harm to aquatic life forms living on or below the water surface. However, this property has yet to be extensively tested and reported on in the literature. In Figure 1 (C) a small sample of the Aquatain product can be seen in the bottom of the glass jar, as it appears before deployment. Figure 1 (D) depicts the appearance of the Aquatain film once it is applied to a small water surface area.

METHOD AND IMPLEMENTATION

Basic Principles

Evaporation is the process that occurs when molecules of liquid water are transformed from a liquid state to a gaseous state (water vapour). Heat (infrared energy) from incoming direct and diffuse solar radiation imparted to the surrounding air and water helps to increase the total kinetic energy of water molecules at the water surface, which helps to facilitate the onset of evaporation. Evaporation only occurs when water particles have enough kinetic energy (latent heat) to transform from the liquid phase into the vapour phase. The speed of the process of evaporation is dependent upon a variety of different atmospheric and physical properties:

Air flow over the evaporating surface: Without any wind travelling over the top of a water body evaporation rates are low as existing evaporated water vapour is not efficiently removed and remains in a relatively stationary state near the vicinity of the water surface. An example of this effect is the vapour visible above a lake on cool mornings. Differences in vapour density gradually results in an increased concentration of water vapour over the surface of the water body. However, the introduction of uninterrupted air flow across the top of a water body initiates the continuous removal of existing water vapour from the water surface allowing for newly escaping water vapour to take its place, thus enhancing the rate of evaporation. In general, greater average wind velocities allow for higher rates of evaporation*;*

Solar radiation: In an outdoors environment, higher levels of solar radiation, specifically the infrared component of the solar spectrum imparts higher amounts of heat energy to water molecules at the water surface. This gives the water molecules a higher average kinetic energy giving them a greater escape probability*;*

Surrounding relative humidity: If the air surrounding a body of water is already saturated, or close to being saturated, by water vapour or the vapour of another type of foreign substance, the process of evaporation will slow down substantially;

Water purity: Generally, water containing both organic and inorganic impurities will evaporate at a slower rate in comparison to fresh water free of any pollutants;

Water temperature: Water molecules present in a body of water subjected to higher temperatures naturally have a higher average kinetic energy which increases their ability to break free from the water surface*;*

Local pressure: Lower local atmospheric pressure allows for more water molecules to escape from the water surface as they are less inhibited and blocked by opposing atmospheric pressure*;*

Surface area: Water spread out over a greater surface area will evaporate at a faster rate as more surface molecules are present and available to be excited into evaporation.

In order to reduce and eliminate the substantial amount of effort and time required to record and process accurate evaporation measurements in real-world locations, many models have been developed over the last fifty years in order to predict and determine evaporation rates in a multitude of different aquatic environments over varying temporal intervals. As the experiments for this exercise will most likely be completed indoors in a school laboratory environment it is simpler to an evaporation model that does not require any solar radiation energy input data. The following model (the Smith-Lof-Jones equation) has been selected from the literature as it is mathematically straight forward in nature and as a result should be relatively easy for students to use. The Smith – Lof – Jones equation for evaporation in outdoors swimming pools (Smith, Lof and Jones, 1994) is given as:

$$E = \frac{(30.6 + 32.1 \times U)(P_W - P_A)}{\Delta H}$$

where E is the evaporation rate in kilograms per metre squared per hour, U is the wind speed propagating over the water surface in metres per second, P_W is the saturation vapour pressure for the specific water temperature in units of mm Hg, P_A is the saturation vapour pressure at the air dew point temperature in units of mm Hg and ΔH is the latent heat of water for the specified water temperature in the tank in units of kJ per kg.

Equipment

Several common items are required to run this experiment successfully. It is necessary to obtain a rigid water container with a depth no more than 300 mm, such as the one depicted in Figure 2 (A). It is very important that the water container chosen is rigid, as a flexible water container may change shape over the trial period as evaporation occurs, which will lead to inaccurate water level measurements. Make sure that the water used is clean and free of any visible particulates such as dirt and dust. Also required is a standard household fan capable of delivering a variety of different wind velocities. It is preferable that the fan can provide up to or more than three different settings as several wind speeds will need to be investigated in order to derive an accurate relationship between evaporation and wind velocity. Make sure that the fan propeller assembly can be positioned in such a way so it can be placed just above the water surface at one end of the rigid container (as shown in Figure 2 (A)). To do this it might be necessary to prop the rigid tank up on bricks or blocks. The fan angle of attack should only be steep enough so that the wind is evenly distributed across the entirety of the tank. Evaporation can be monitored by simply measuring the change of the water level in the tank at the start and at the end of the experiment. This can be done by using either a ruler or with a laser distance measurement device such as the Ultrasonic Laser Distance Meter (available from http://stores.channeladvisor.com/superonlinestore/items/item.aspx?itemid=1052279&utm_source=getprice&utm_medium=cpc) set at a constant height with a laboratory jack (or a similar apparatus) for the initial and final water level measurements. Using a laser distance measurement device will provide a much greater level of accuracy for the initial and final evaporation measurements in comparison to the ruler, as the use of a ruler in water is prone to parallax error. It is important not to place the ruler in the tank at any time during the experimental period. Water may stick to the ruler and drip off to the side, which may lead to an erroneous final water level measurement.

If it is possible, a water container and a fixed digital distance gauge (available from www.measumax.com) should be combined and used as a control standard to compare the wind driven evaporation to a static case for each particular experiment. If a digital distance gauge is not available, then a ruler can be used as a replacement, however some measurement precision will be lost. A picture of a standard/control water container made and used by the authors is displayed in Figure 2 (B).

Air temperature, water temperature and humidity are three environmental/atmospheric parameters that must be monitored throughout each trial. Both air and water temperature can be measured using a bulb thermometer. For continuous measurements of air and water temperature and humidity at a higher level of precision

Gemini Tiny Tag data loggers (www.geminidataloggers.com*)* or Lascar Electronics EL-USB-2 data loggers (www.lascarelectronics.com) can be employed. Wind velocity from the fan can be measured using a DSE mini air speed pocket meter (http://dicksmith.com.au/product/Q1301/dse-mini-air-speed-and-temperature-pocket-meter).

Figure 2 – (A) Example fan and tank configuration. The large graduated tube placed in the left hand side of the tank was used to make a simple estimate of the water level before and after each experiment. (B) Standard/control evaporation measurement container (clear glass) on top of which sits a fixed digital distance gauge.

Measurement of Evaporation

1. Apply the fastest wind speed to the rigid tank filled with water. The tank should be set up in a room with a controlled temperature. A store room with continuous air conditioning would be ideal. Make sure that the students take note of the exact water level at the start of the experiment;
2. If a standard/control evaporation measurement container is in use, make a note of the water level at the beginning of the experiment. Also, don’t forget to check the standard/control water level at the end of each experiment;
3. Make sure to start and continue measuring wind speed, humidity, ambient temperature, water temperature throughout each trial;
4. Measure the evaporation occurring after a period of 24 to 48 hours using an appropriate ruler or a laser distance meter. If necessary, the recommended trial time period can be reduced from the 24 to 48 hour interval down to anywhere from 1 to 10 hours (i.e. throughout the duration of the school day). However, as there will only be a limited amount of time for evaporation to occur, a laser distance meter will almost certainly be necessary to measure the small changes in water level;
5. Following the fastest wind speed experiment, measure the evaporation occurring over a period of 24 to 48 hours (or from 1 to 10 hours) for the remainder of the speed settings available from the fan. Also, run a final static trial with no wind applied to the water tank in order to obtain a baseline evaporation value;
6. Start another series of experiments by applying the WaterSavr monolayer to the surface of the water in the tank. Ensure that the spread of the monolayer is even and that no conglomerations are formed on the water surface before delivering the wind. Experiment with a range of different spreading ratios to determine which one is the best;

7. Measure evaporation occurring over a period of 24 to 48 hours (or from 1 to 10 hours) for each of the different fan speed settings using either a conventional or digital ruler. As instructed in step 5, make sure to complete a final static trial with no wind applied to the water tank so a baseline evaporation value can be obtained;

NOTE: It is very important to ensure that the tank is cleaned with fresh water thoroughly between each experiment. Both WaterSavr and Aquatain have adhesive-like properties that will make them stick to the walls of the tank. If chemical film/ monolayer remnants from previous experiments are not adequately removed, the evaporation data recorded in future experiments could be compromised.

8. Start a third and final series of experiments by applying the Aquatain chemical film to the surface of the water in the tank. Ensure that the spread of the Aquatain is even and that no sizeable globules are created on the surface of the water before starting up the fan. As with the WaterSavr experiments, try a range of different spreading ratios to determine which one provides an adequate amount of coverage;
9. Measure evaporation occurring over a period of 24 to 48 hours (or from 5 to 10 hours) for all of the fan speed settings using either a conventional or digital ruler. As was the case in both step 5 and step 7, ensure that a final static trial with no wind applied to the water tank is completed.

Data Analysis

Students may choose to complete the graphical and modelling work required for this exercise on paper or by using spread-sheeting software like Microsoft Excel. However, it is probably best to use spread-sheeting software as it allows for the rapid determination of plotted gradients and correlation coefficient, R^2 information. The data analysis phase should be completed in the following order:

1. Plot average temperature values for each experiment on the same graph. An example set of temperature measurements made by the authors is displayed in the bar graph shown in Figure 3;
2. Plot average humidity values for each experiment on a separate graph to the temperature graph. An example average humidity bar graph is depicted in Figure 4. Both the temperature and humidity data can be displayed on the same graph by using a secondary axis;
3. Complete a bar graph showing the static evaporation measurements for each experiment measured in the standard container. Figure 5 shows an example bar graph of static evaporation measurements made for each separate experiment in the standard container previously displayed in Figure 2. Make sure the values obtained for each experiment are distinguishable by using different colours or shading patterns for each bar. Ensure that the evaporation measurements are converted to units of kg/hour. This conversion can be made by following these steps:
    - A. Multiplying the final evaporation measurement (in mm) by the surface area of the container (to provide a result in units of mm^3);
    - B. Divide this result by 10^9 mm^3/m^3;
    - C. Multiply that by 1000 kg/m^3 as 1 m^3 of pure water has a mass of 1000 kg;
    - D. Divide by the total number of hours for the duration of each experiment.
4. Complete a bar graph displaying the final evaporation measurements obtained in the tank after the application of different wind speeds and monolayers for each

separate trial. Figure 6 displays an example bar graph with each evaporation measurement made corresponding to each particular wind speed. Again, make sure the values obtained for each experiment are distinguishable by using different colours or shading patterns for each bar. Also, convert the evaporation measurements to units of kg/hour;

5. Employ the evaporation model to calculate modelled evaporation values for each of the wind speeds measured in the experiments. Make sure the evaporation measurements are converted to units of kg/hour. Example measured and modelled evaporation values are shown in Figure 7. To make calculations easier, students can average out the measured temperature and humidity data and in turn the calculated saturation vapour pressure over the entire experimental time period before insertion into the model. To evaluate the calculations made for saturation vapour pressure the following website can be used: http://www.csgnetwork.com/vaporpressurecalc.html;
6. Plot measured and modelled evaporation values versus wind velocity on the same graph. Make sure all the measured and modelled evaporation data points are converted to units of kg/hour. Set a linear regression line to both sets of modelled and measured values. Make sure to calculate the R^2 value for each regression line in order to obtain a meaningful assessment of the correlation between wind velocity and evaporation;
7. The students can discuss reasons why their measured evaporation data differed from or corroborated with the modelled evaporation data. A discussion should also be performed detailing reasons why one chemical film/monolayer performed better than the other.

As the data analysis work required to properly complete this series of experiments is extensive, it is recommended that students work on it as an extended investigation or extended assessment task.

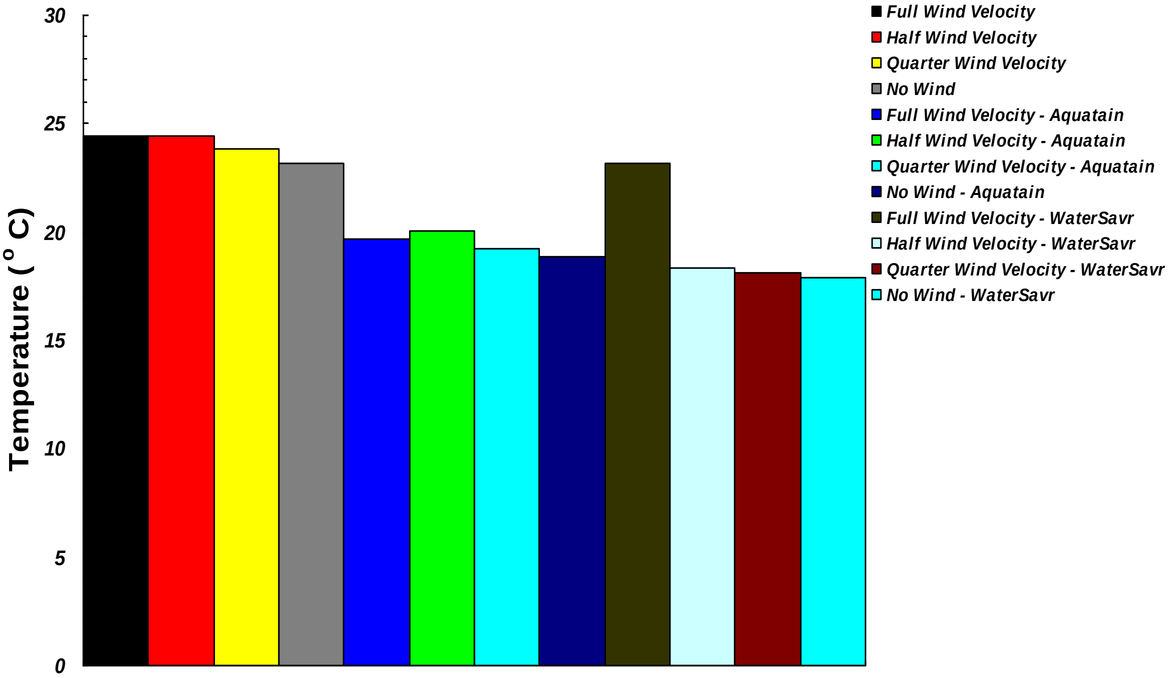

Figure 3 – Average air temperatures measured over the duration of each experiment.

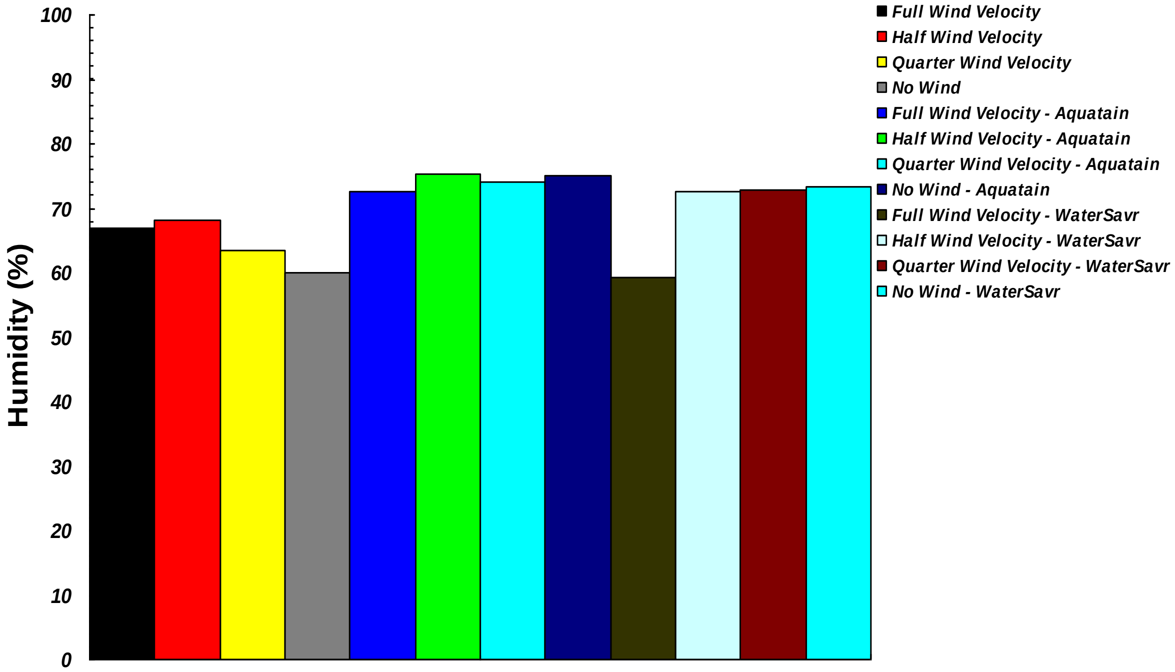

Figure 4 – Average humidity values measured over the duration of each experiment.

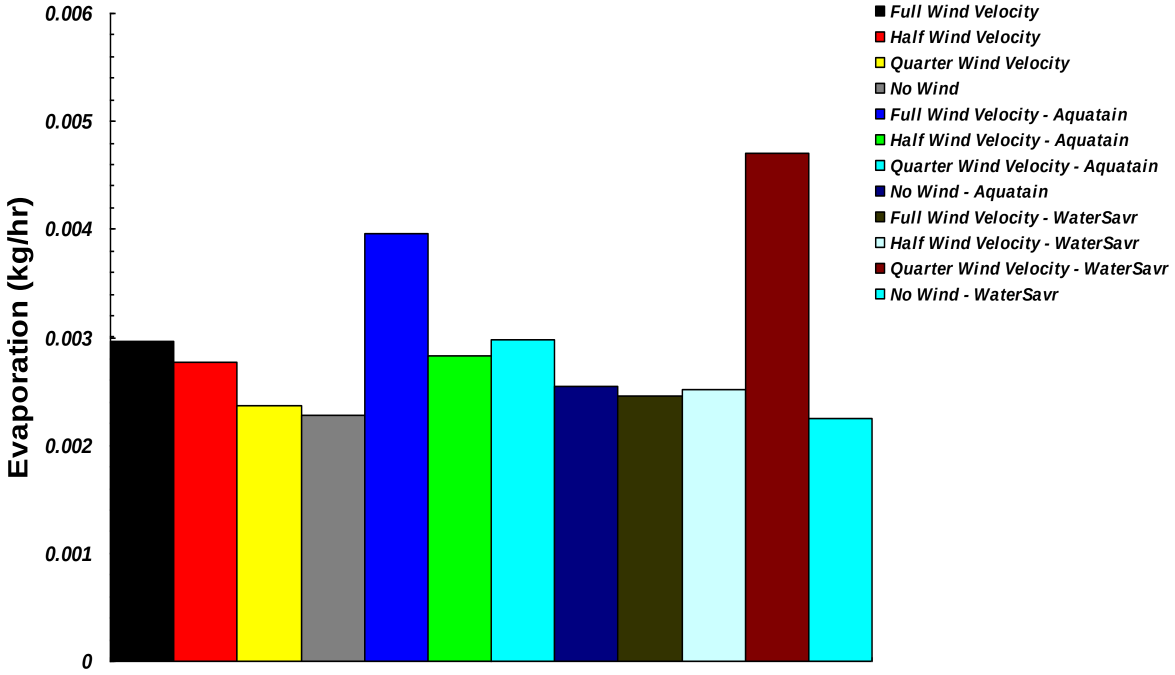

Figure 5 – Standard evaporation container measurements for each experiment measured in units of kg/hour.

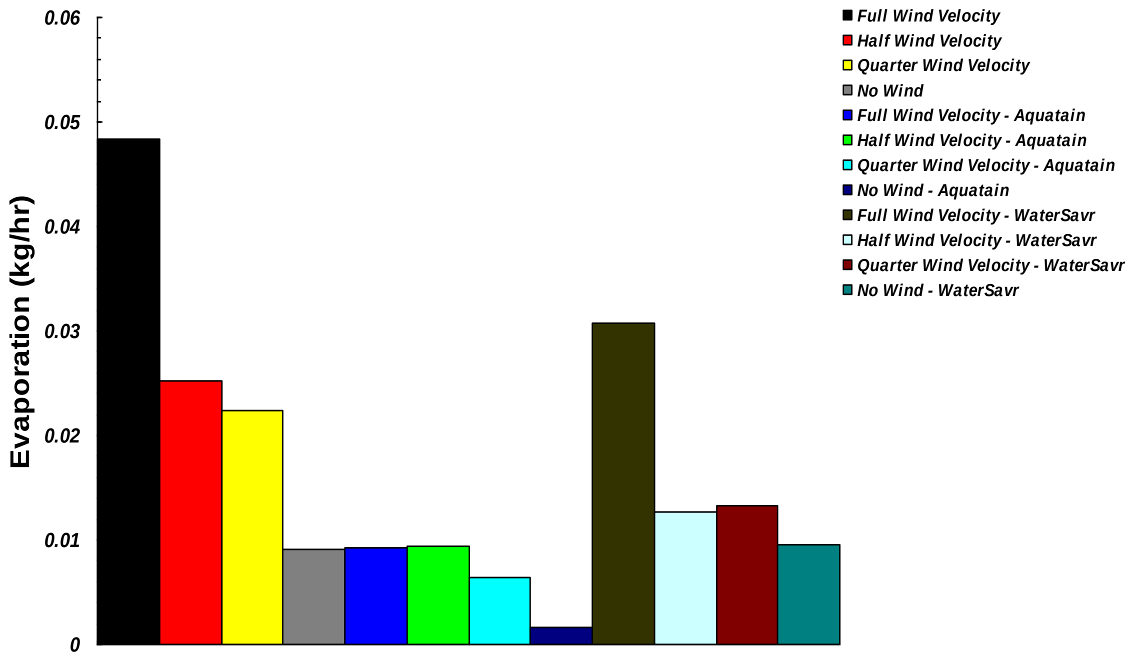

Figure 6 – Evaporation with changing wind velocity for each experiment measured in units of kg/hour.

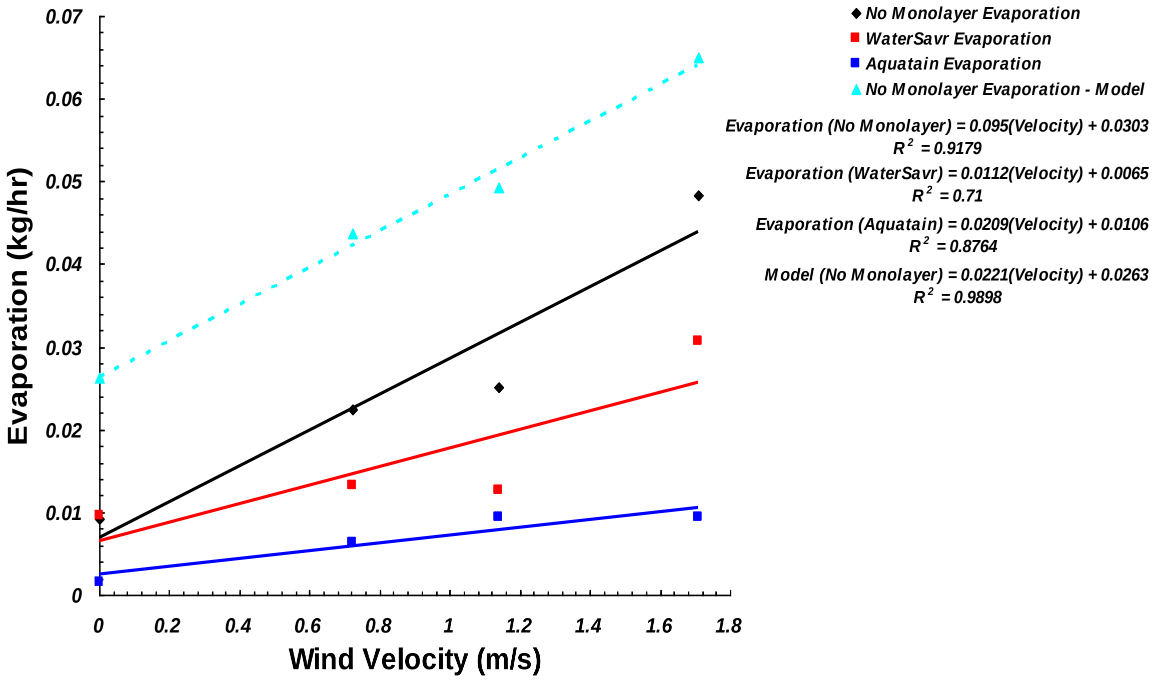

Figure 7 – Evaporation measured for each experiment with (solid trend line with diamond data points) and without chemical film/monolayer application (solid trend lines with square data points) compared to the model output (dashed trend lines with triangle data points) in units of kg/hour.

CONCLUSION

This article has provided Year 11 and Year 12 Physics and multi-strand science teachers a series of relatively simple practical exercises from which they can show students how real-world evaporation measurements can be made and compared to modelled evaporation data using a variety of atmospheric and environmental parameters such as air temperature, water temperature, humidity and wind velocity. By doing this the students can appreciate how evaporation measurements can be difficult to obtain in uncontrolled conditions and how chemical films/monolayers such as WaterSavr and Aquatain can be deployed on the water surface to reduce the at times extreme levels evaporation that are prevalent across the greater Australian continent. Students are also introduced to several new mathematical concepts such as how to employ a detailed mathematical evaporation model. The activity provides students with the opportunity to familiarise themselves with statistical concepts such as using linear regression and developing data interpretation skills. In addition, from this practical work students are given the opportunity to further extend their scientific literacy and numeracy skills alongside expanding their computational skill set by producing graphs and conducting simple data analysis routines using computer software.

Teachers may wish to extend this study over the 24 to 48 hour time period as stated in the methodology to over a week or over a month if possible. Evaporation can be continuously monitored inside a bigger outdoors tank in order to enhance the level of realism. A more accurate method of measuring water level changes will most probably be required (such as installing a simple standalone water pressure sensor). The teacher can substitute clean tap water with another type of water such as that sourced from a dam, creek or the ocean. The difference in evaporation levels between clean tap water and water sourced from natural locations can then be deduced and discussed.

Links to the Curriculum

The activity presented integrates three areas of the science curriculum, namely physics, chemistry and agricultural science. The activity provides sufficient detail to allow application of mathematical modelling to explain real world phenomena that have direct influence on our sustainable use of finite water resources. Thus, the activity demonstrates direct relevance to the earth and environmental science curriculum focus for students in years 11 and 12 as outlined in the National Curriculum Board's draft Australian Science Curriculum (NCB, 2010). The detail developed for this activity provides sufficient information for students' to develop their understanding of water and its management. Students are also introduced to techniques applied in general climate and atmospheric research. However, the materials required to perform the activity successfully are readily available and require no specialist equipment. Simple measurements of the evaporation of water under different wind speeds and with different chemical monolayers have application also for younger learners beginning studies in science.

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