1499

Review and Recommendations for Charlotte Harbor PAR Data, October 2008 – May 2010

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MARINE LABORATORY

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Table of Contents

Figures and Tables

Background

Photosynthetically active radiation (PAR) data for Charlotte Harbor have been the subject of a number of recent investigations to address seagrass-related water clarity targets for the Harbor (Janicki Environmnetal, Inc., 2009) as well as the spectral nature of attenuation (Dixon et al., 2010). Clarity targets work indicated that attenuation coefficients for many stations (computed as the slope of the linear regression of natural log transformed raw PAR data as a function of depth) were exceptionally noisy (low r^2 values) and were excluded from analyses (M. Wessel, personal communication). Despite excluding noisy values, many stations, beginning in mid- to late-2006, apparently had computed attenuation coefficients substantially less than the literature values for attenuation by pure water alone (Pope and Fry, 1997; Dixon et al., 2010). The appearance of attenuation values below theoretical minima was coincident with a change in methodology from multiple measurements at multiple depths to fewer measurements with paired sensors and was persistent through at least mid-2008. As sensors were seldom, if ever, relocated on the measurement apparatus (Ms. Sarah Erikson, personal communication), the low values were speculated to be the result of a disparity in sensor calibrations.

The Southwest Florida Water Management District (SWFWMD) subsequently asked Mote Marine Laboratory to perform data entry and initial quality review of more recent data and to provide recommendations for data entry and processing. Data were available from 500 stations and 1521 station-depths, with 146 instances of data recorded at the same depths with different sensors.

Measurement Techniques

Equipment generally employed for PAR measurements consists of a LI-COR 1400 data logger, and up to three cosine quantum sensors, one designed for use in air (LI-190) and one or more submersible sensors (LI-192). Data loggers have three BNC terminals to which the sensors are connected. Cables extend from the bottom of the sensors, requiring water column depths in excess of the depth of the plane of measurement of the lower sensor by 0.1-0.2 m, depending on the apparatus used to submerge sensors. Data logger setup requires that the sensor-specific calibration factors (used to convert sensor electronic output to the correct engineering units of $\mu E\ m^{-2}\ s^{-1}$) be stored in the channel to which the cable for that sensor is connected. Display of the various channels is accessed through a two line display on the data logger which allows the air reading to be viewed and recorded. The display is then scrolled to the two submerged readings. Measurement techniques should also include keeping all sensor faces as horizontal as possible, working on the sunny side of the boat, having minimum obstructions which obscure skylight, shade, or provide reflected light to the air sensor (i.e. from a large light-colored boat superstructure), avoiding similar reflections from the boat hull onto the upper submerged sensor, avoiding boat shadow, avoiding instrument self-shading, and either lowering submerged sensors to minimum depths or using a moving average of PAR to reduce the effects of wave focusing.

Field sheets for samplings conducted in Charlotte Harbor and Lemon Bay by Florida Fish and Wildlife Conservation Commission personnel were supplied by SWFWMD and selected parameters entered into a data base (date, grid or station, time, cloud cover, wind speed, depth overall, secchi depths, readings of PAR in air, and depths and values of PAR measured with submersible sensors). (Other *in situ* data had been previously addressed by field, laboratory, or SWFWMD personnel.) Each group of readings (an air and two submerged PAR measurements) were collected as close in time as possible, but instrument logging functions were not employed. Sensor cross calibrations were not routinely performed until June 2010.

For the period reviewed, PAR data were collected by two different methods. From October 2008 to July 2009 (Method A), three data points per station were collected as a group using an air sensor, and two submersible sensors. Submersible sensors were separated by either 0.5 or 1.0 m depending on station depth overall, with the upper sensor 0.5 m below the water surface and the lower sensor at either 1.0 or 1.5 m.

Between August 2009 and May 2010, a several groups of PAR readings were performed at a station if depths permitted (Method B). Each group consisted of a value from an air sensor and values from an upper and a lower submersible sensor, separated by a fixed 0.5 m. Protocol was to perform group readings with the upper sensor located successively at 0.5 m, 1.0 m, and 2.0 m below the water surface. The elevation of the paired sensors was sometimes varied slightly in response to station depths. When stations are shallow (less than 1.5 m), Method B is equivalent to Method A, as only one group of readings is performed. Having PAR measured at the same depth with different sensors (to compare sensor cross calibrations) was only available for data collected with Method B.

Attenuation coefficients can be computed by several approaches to these data. When only one group of data is collected, then the diffuse attenuation coefficient (K_d) is computed as:

$$K_d = -\mathit{ln}\,(I_{d2} / I_{d1}) / (d_2 - d_1)$$

where d_1 and d_2 are the depths of the faces of the upper and lower sensors, respectively, and I_{d1} and I_{d2} are the incident irradiances measured at the respective depths. When several groups of data are collected at various depths of a station, K_d can be calculated for each group as above, and the several K_d values averaged to represent conditions for the entire water column. Lastly, the attenuation coefficient is considered to be more accurately computed (Kirk, 1994) as the negative slope of a linear regression of natural log transformed PAR data as a function of depth, or

$$K_d = (n * \sum (d * \mathit{ln}(I)) - (\sum d)*(\sum \mathit{ln}(I))) / (n * \sum (d^2) - (\sum d)^2)$$

Air Normalization

The methods for computing attenuation coefficients, as presented above, depend on all measurements made under conditions of identical incident irradiance. If this is not possible, as under scattered cloud conditions, then data should be normalized to some selected irradiance. The basis of the air correction is the fractional nature of attenuation (*x* fraction removal of PAR per unit of distance). As an example, if incident irradiance at the water surface (air reading) declined from 2000 to 1000 μE m^{-2} s^{-1}, then a submersible reading at a fixed depth which had been 500 μE m^{-2} s^{-1} would be expected to decrease by the same proportion to 250 μE m^{-2} s^{-1}. Normalization presents PAR data as if all were collected under identical incident PAR irradiance and removes the variations due to changing cloud cover. The normalization process does not account for subtle spectral variations associated with transitions from clear to partly cloudy to overcast conditions. (Initial computations of attenuation coefficients for review of water clarity targets [Janicki Environmental, Inc., 2009] did not perform air normalizations. It is possible that correcting for air variations would reduce some of the poor correlations observed.)

Air normalization addresses between-group variations in surface irradiance. The inherent assumption, however, is that the air and two submerged readings are collected simultaneously, i.e. with no within-group variation in incident irradiance. If cloud conditions are changing rapidly and if PAR values are recorded manually with finite time intervals between, then the air reading for a group may not accurately represent the conditions under which other group PAR measurements are made. Electronic logging of all PAR channels simultaneously would remove this potential source of error.

Air normalization can be carried out to any irradiance value. A single value can be selected for a station, for a day, or for an entire data set. For this work, all data were normalized to a single air reading (arbitrarily set at 2000 μE m^{-2} s^{-1}) by multiplying the data in each group by a factor computed as

$$\text{Air Correction Factor} = 2000 \,/\, \text{group air reading.}$$

Sensor Cross Calibration

In order to assess sensor calibrations and potential bias between upper and lower sensor responses, normalized data collected at a station with an upper and a lower sensor but at the same depths were compared for percent agreement. Excluding one outlier that appeared to be a recording error, median agreement of upper divided by lower sensor values was 116%, with a mean of 123% and a range of 33-347%. The 5th and 95th percentile values of agreement were 68% and 198%, respectively. Cumulative distributions of percent agreement data (Figure 1) illustrate the positive bias.

Distribution of the acceptable (90-110%) percent agreement values appear unrelated to date, sun angle (time), station (Grid #), attenuation coefficient (K_d), secchi depths, or % cloud cover (Figures 2-8), eliminating step trends in technique, or light, water column, or sediment properties as the source of the lack of agreement between sensors.

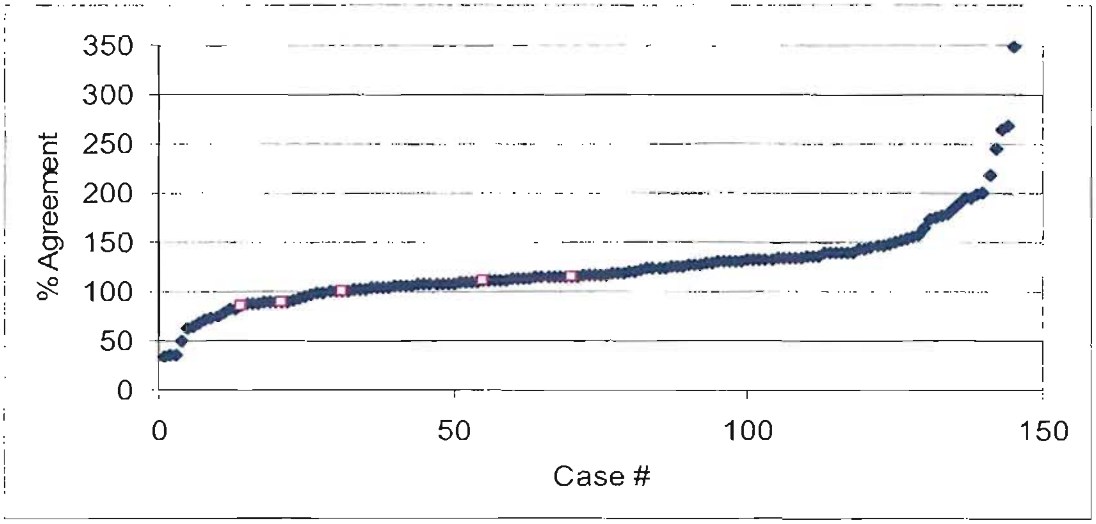

Figure 1. Cumulative distribution of percent agreement between upper and lower PAR sensors (solid). Open squares illustrate 85, 90, 100, 110, and 115% agreement levels.

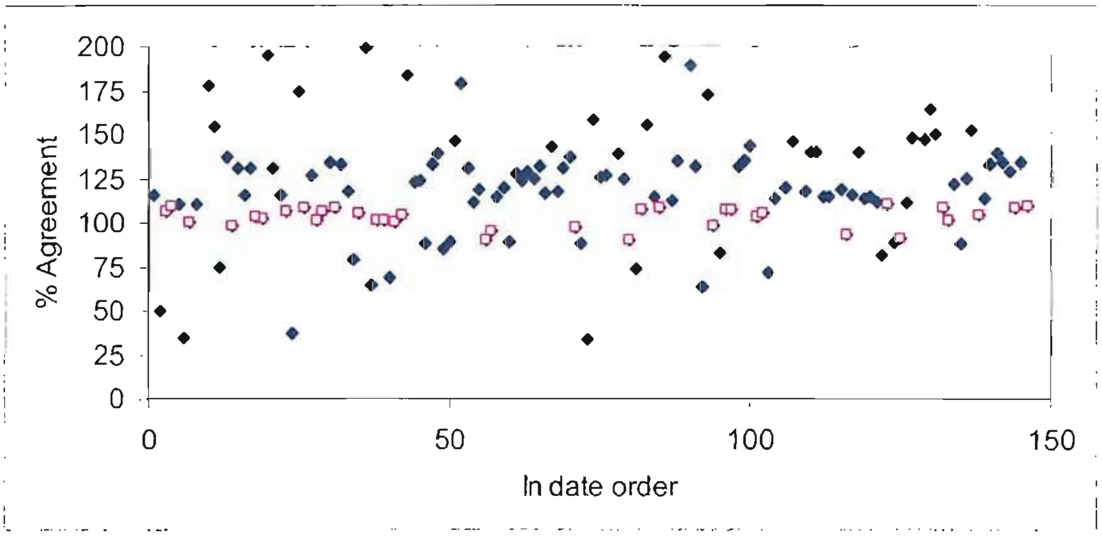

Figure 2. Distribution of percent agreement between upper and lower sensors in order by date of collection. Open squares indicate agreement between 90-110%.

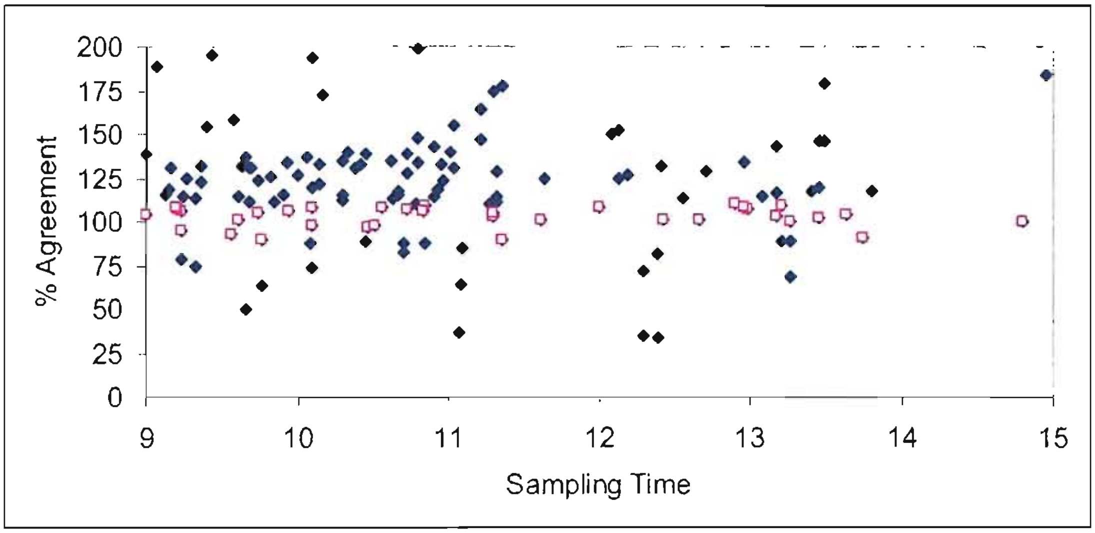

Figure 3. Distribution of percent agreement between upper and lower sensors as a function of sampling time. Open squares indicate agreement between 90-110%. Open squares indicate agreement between 90-110%.

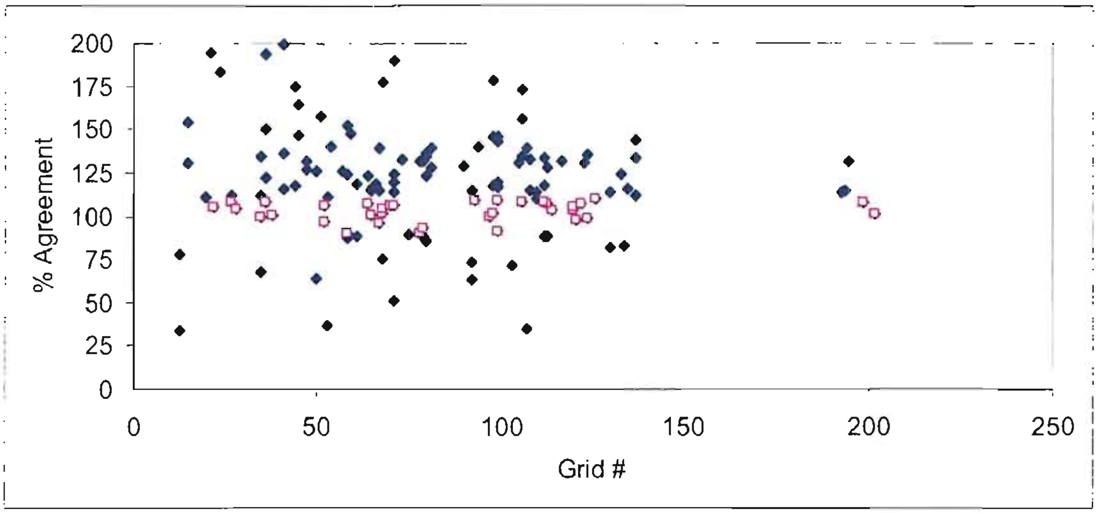

Figure 4. Distribution of percent agreement between upper and lower sensors as a function of station Grid #. Open squares indicate agreement between 90-110%.

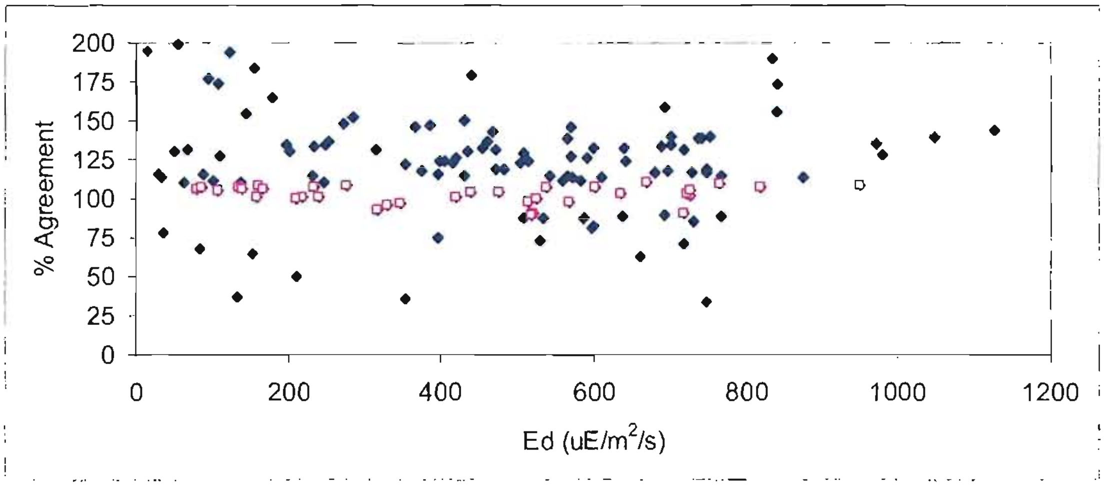

Figure 5. Distribution of percent agreement between upper and lower sensors as a function of measured PAR intensity. Open squares indicate agreement between 90-110%.

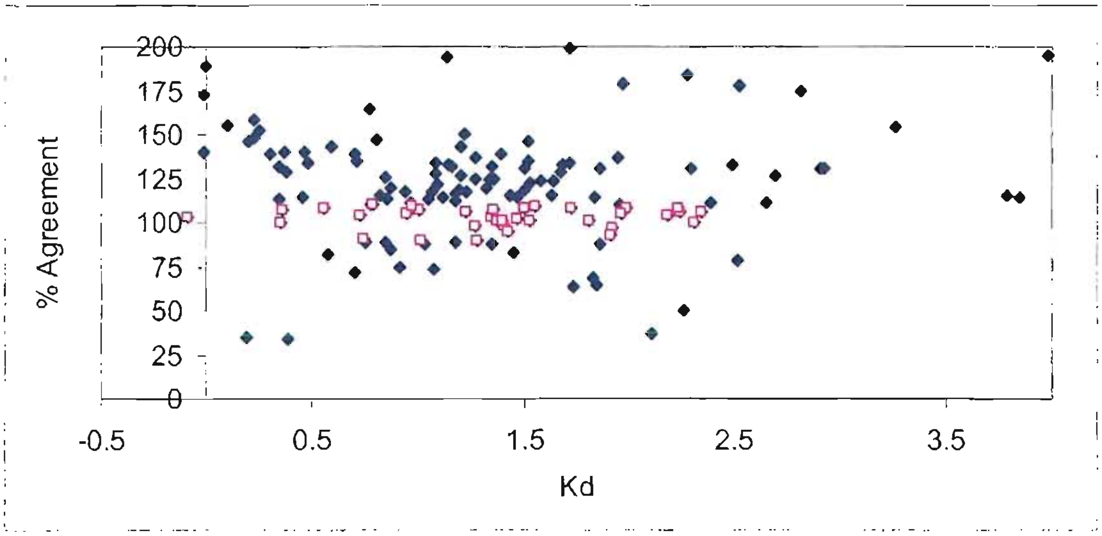

Figure 6. Distribution of percent agreement between upper and lower sensors as a function of attenuation coefficient (K_d) computed from the 0.5 and 1.0 m readings. Open squares indicate agreement between 90-110%.

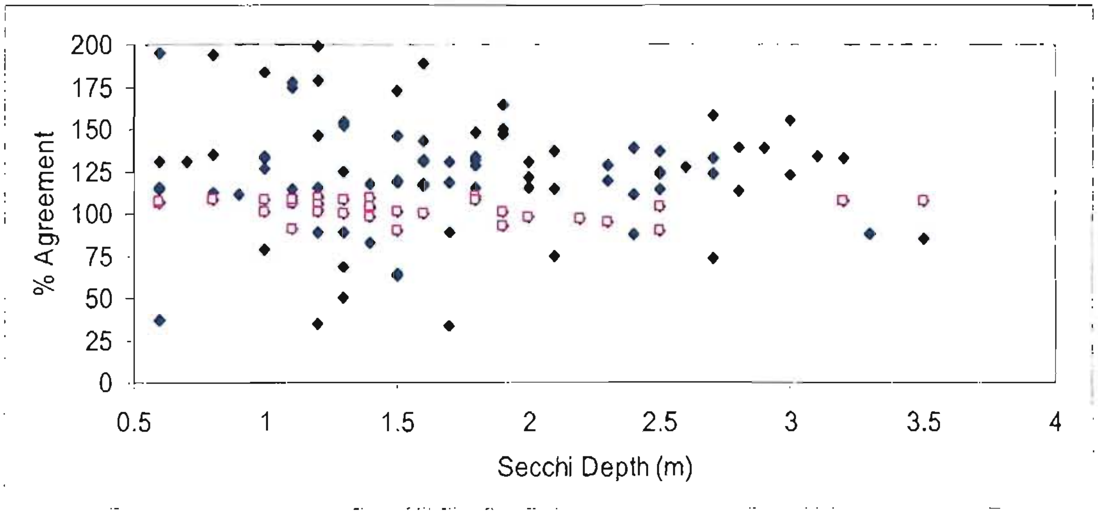

Figure 7. Distribution of the percent agreement between upper and lower sensors as a function of secchi depth. Open squares indicate agreement between 90-110%.

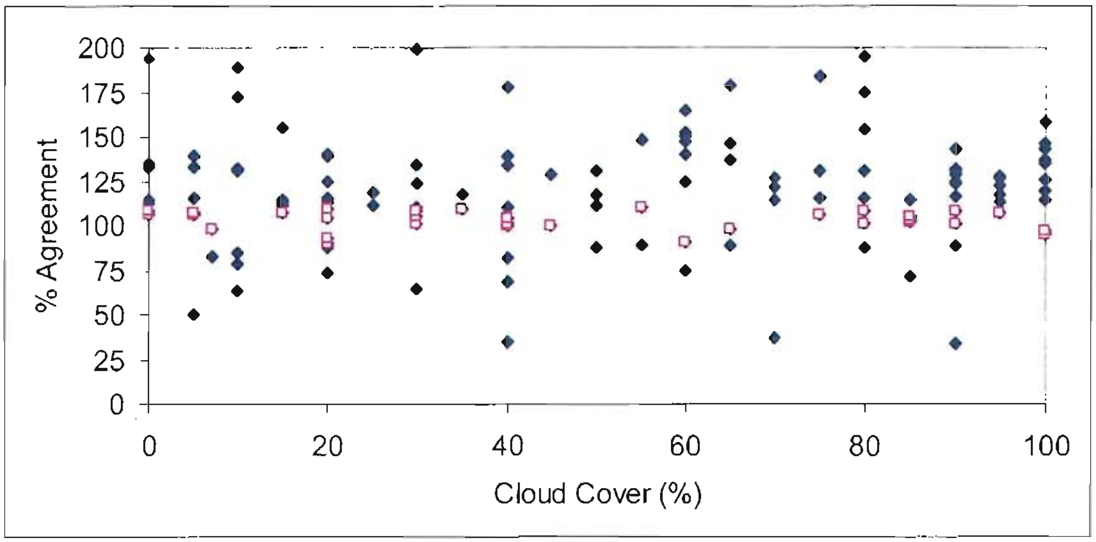

Figure 8. Distribution of the percent agreement between upper and lower sensors as a function of percent cloud cover. Open squares indicate agreement between 90-110%.

Recently, sensor cross calibrations performed in air between June 2010 and August 2010 (*n*=6) indicate that sensors presently agree on average at 108%, ranging from 97 to 120%. These results further support the supposition that discontinuities in sensor calibrations were the source of the bias in percent agreement. Unfortunately, assuming that sensors have not been moved (lower exchanged for upper, etc.), normalizing data between sensors would result in even lower attenuation coefficients and would not resolve the issue of attenuation coefficients below theoretical minima as observed in 2006-2008 data.

All 146 instances of readings with multiple sensors at the same depths were graphically reviewed. In many instances, and despite the overall positive bias of the upper sensor relative to the lower sensor, agreement between sensors was excellent; 35 of the 146 comparisons agreed within 90-110%, and 57 of 146 agreed within 85-115%. In one example, plotting air corrected but otherwise unaltered irradiance as a function of depth (Figure 9) displays a smooth curve of the expected exponential loss of PAR with depth, and reasonable agreement (110%) of the upper (Series 1) and lower (Series 2) readings at 1.0 m. Natural log transformations of these data result in a highly linear relationship (Figure 10). In this example, attenuation coefficients (negative slopes) between the two points of each group were 1.96, 1.67, and 1.61 m^{-1}, when the upper sensor was at 0.5, 1.0, and 2.0 m respectively, and illustrated the progressive decline in attenuation coefficient which occurs as a result of the selective spectral removal of selected wavelengths of light. Using all PAR data in a regression, the overall attenuation coefficient was 1.71 m^{-1}, and quite comparable to the mean of 1.74 m^{-1} computed as the mean of 1.96, 1.67, and 1.61 m^{-1}.

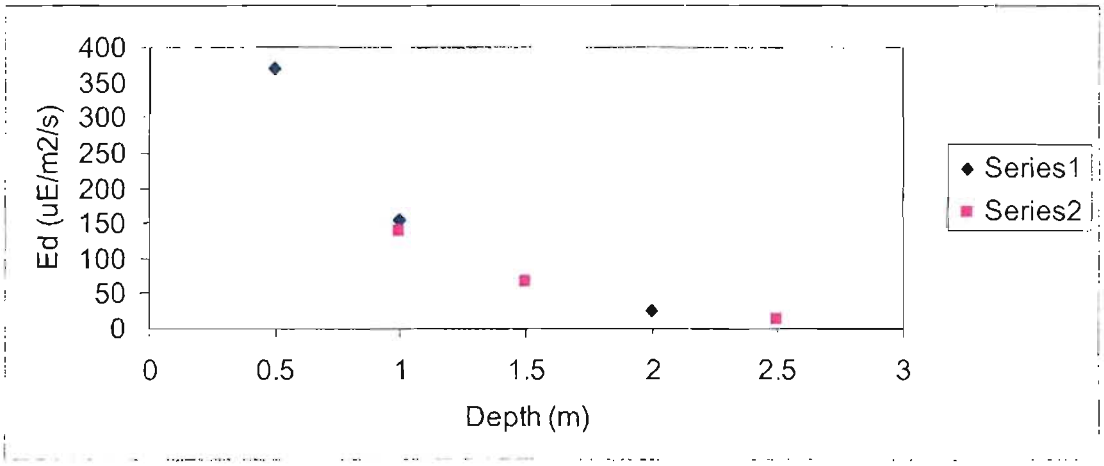

Figure 9. Air-normalized PAR as a function of depth, August 12, 2009, Grid # 053. Upper sensor is Series 1, lower sensor is Series 2.

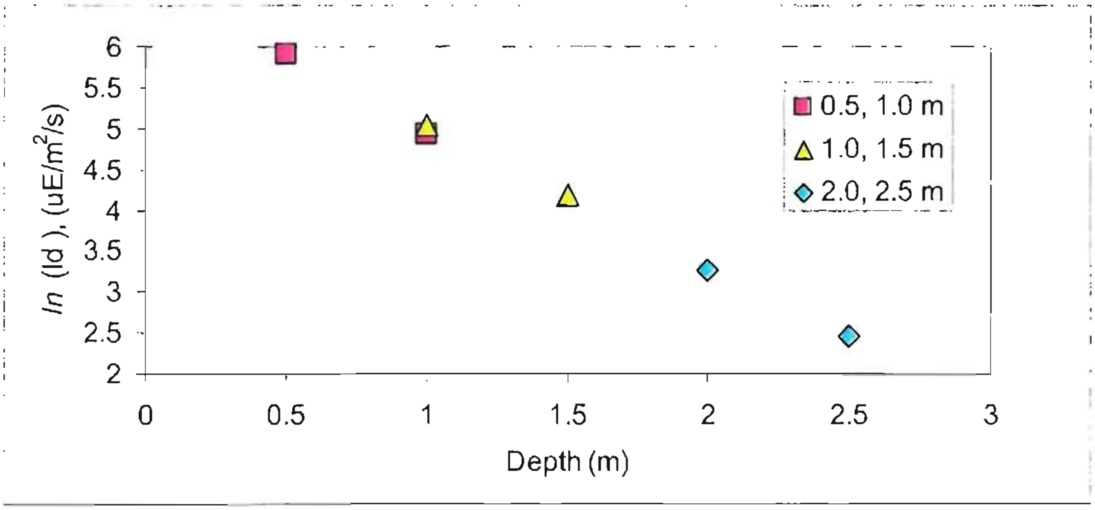

Figure 10. Natural log transformed, air-normalized PAR as a function of depth, August 12, 2009, Grid # 053.

Adjustment for sensor cross calibration (dividing upper sensor data by 1.16, the median agreement), results in data of a very similar appearance to Figures 9 and 10 (Figure 11). Recomputed attenuation coefficients from paired data were 1.66, 1.38, and 1.32 m^{-1} with a mean of 1.45 m^{-1}, and a regression slope-derived K_d of 1.67 m^{-1}. Numerically, dividing all surface sensor data by 1.16 will reduce K_d values calculated from paired PAR data by ~0.15 m^{-1} when sensors are separated by 1.0 m and by ~0.3 m^{-1} when sensors are separated by 0.5 m. The effect on slope-derived data is comparatively minimal but will depend on the number data points and the depth values, due to the proportionally larger influence on regression parameters by points at the extreme ends of the *x*-distribution.

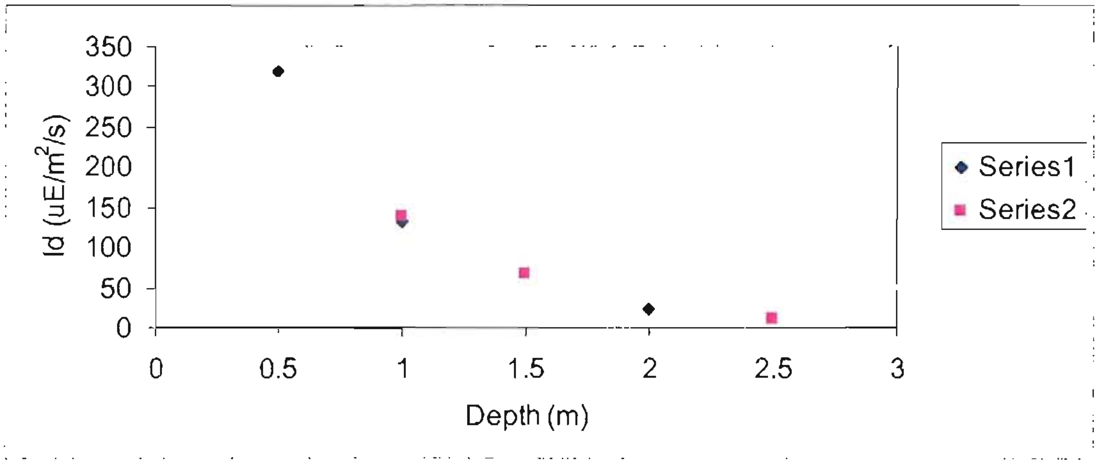

Figure 11. Air-normalized PAR as a function of depth, August 12, 2009, Grid # 053. Upper sensor is Series 1, lower sensor is Series 2. Upper sensor data have been divided by 1.16 to normalize between sensors.

In other instances, agreement between upper and lower sensors was reduced (Figure 12), and normalization between sensors does not substantively improve appearances (Figure 13). There are a number of potential sources for both the lack of a smooth exponential relationship and a lack of agreement at a given depth, but highly variable air readings for the three groups, ranging from near 1000 to near 2000 μE m^{-2} s^{-1}, make it likely that within-group air variations may be present and were not captured when data were manually recorded.

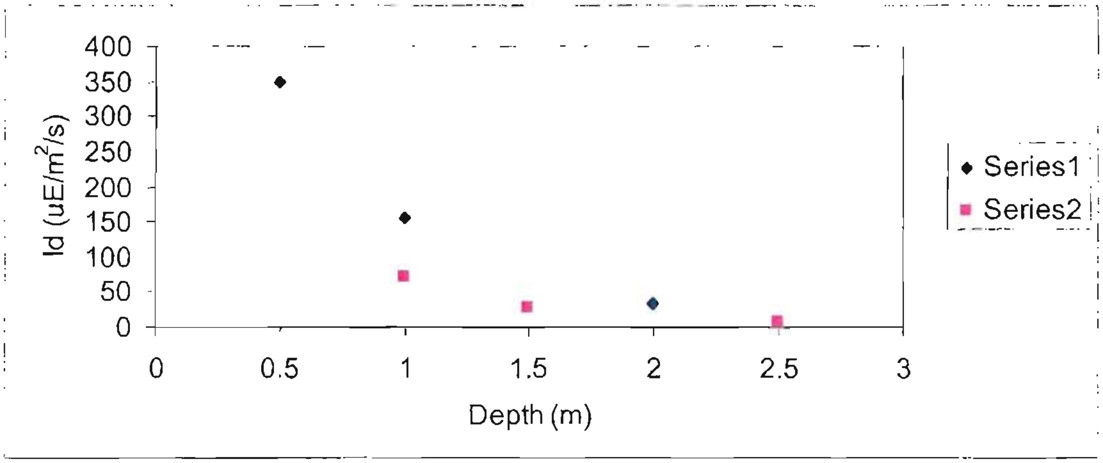

Figure 12. Air-normalized PAR as a function of depth, March 10, 2010, Grid # 190. Upper sensor is Series 1, lower sensor is Series 2.

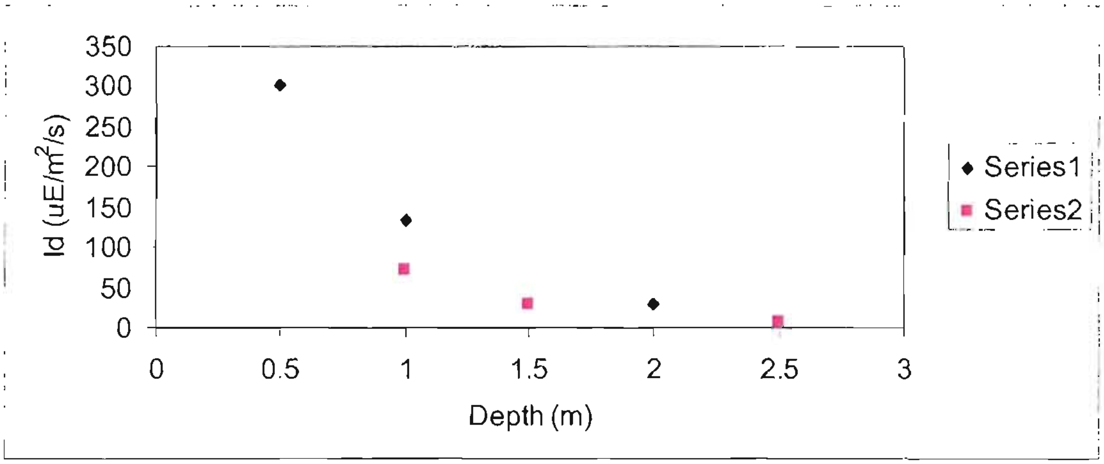

Figure 13. Air-normalized PAR as a function of depth, March 10, 2010, Grid # 190. Upper sensor is Series 1, lower sensor is Series 2. Upper sensor data have been divided by 1.16 to normalize between sensors.

In a third example (Figure 14), all air readings were very consistent (1345, 1363, and 1347 μE m^{-2} s^{-1}) under an apparently stable 90% cloud cover. Agreement between air-corrected upper and lower sensors was acceptable, but the smoothness of the exponential relationship could be improved (Figure 15) if the deepest pair of readings had been made at 1.4 and 1.9 m instead of at 1.7 and 2.2 m as recorded. This adjustment in depth is arbitrary, and field crews can identify whether the difference between actual and recorded depths is likely. On other occasions, there may have been slight differences between recorded and actual depths based on 0.5 and 1.0 m readings being made when water column depths were 1.0 m, or when any reading was less than 0.1 m shallower than overall water column depth. Alternatively, however, the swing of an anchored vessel could certainly permit slightly deeper depths to be encountered after the depth overall was recorded. Any differences between actual and recorded depths of PAR measurements would not affect K_d values computed from a single group of readings or as the mean of K_d values from each group, but would affect K_d values derived from regression slopes.

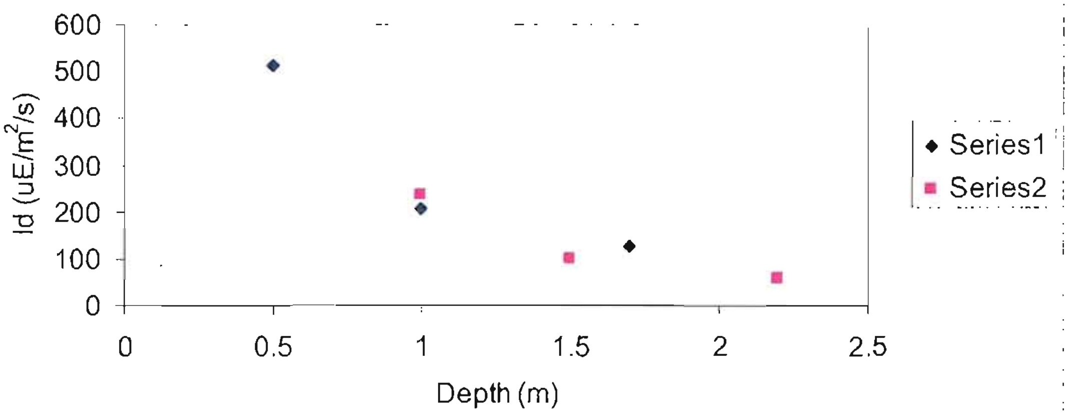

Figure 14. Air-normalized PAR as a function of depth, May 4, 2010, Grid # 038. Upper sensor is Series 1, lower sensor is Series 2. Upper sensor data have been divided by 1.16 to normalize between sensors.

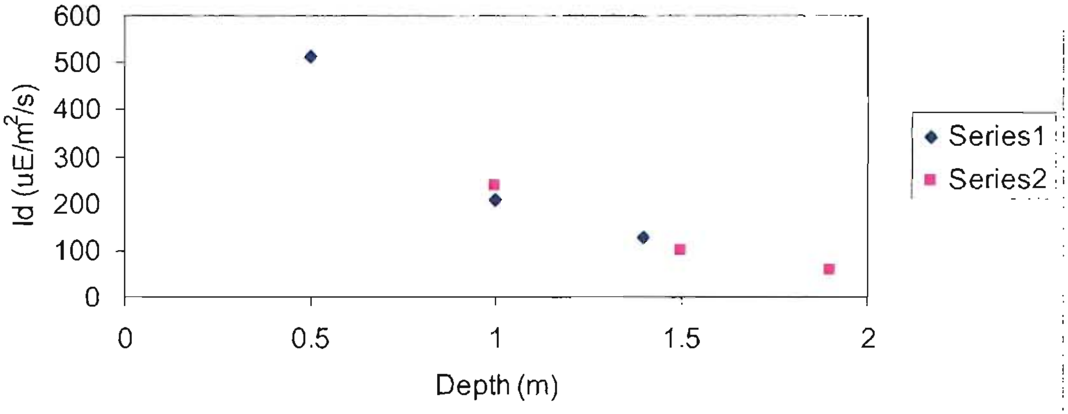

Figure 15. Air-normalized PAR as a function of depth, May 4, 2010, Grid # 038. Upper sensor is Series 1, lower sensor is Series 2. Upper sensor data have been divided by 1.16 to normalize between sensors. Lower depths arbitrarily adjusted to create a smoother exponential relationship.

Potential Errors

The potential sources of error in PAR measurements are listed in Table 1, together with a relative assessment of the potential impact on the various methods of K_d computations, and whether data corrections are possible. Many error sources are highly unlikely for all but the most inexperienced field personnel but are included for completeness.

Based on the relative impact of various errors, the computation of K_d from a single pair of submerged readings is the least robust to error and provides little opportunity to review and correct data after the fieldwork is completed. This is the default technique of the present field protocol for stations with depths less than 1.5 m. Field attenuation data for these shallow stations are likely more variable than those computed from measurements at multiple depths. Attenuation coefficients calculated as the mean of several group K_d values are more resistant to errors in recorded measurement depth, or random errors in a group air reading, but depend on having multiple pairs of data.

Calculations of K_d from regression slopes are in general more resistant to influence from random recording or transposition errors, to changing within-group cloud conditions, and to erratic wave focusing effects. For the regression method of K_d, the impact of errors is greater when data points at the upper or lower end of the depth distribution are affected, when compared to errors in data for the middle depths. A more definitive error analysis could be performed by comparing PAR and K_d values derived from optical model results (based on color chlorophyll and turbidity data) with those recorded in the field.

Recommendations

Existing data should be corrected for varying cloud conditions between measurement groups. Adjustment of data for sensor cross calibration results is also recommended based on median agreement between upper and lower sensors. Based on robustness to a variety of errors, attenuation coefficients should be computed from regression slopes where possible.

For future data collection, training of field staff in the numerical processing of these data is recommended to develop an awareness of the impacts of various errors. Data groups should be collected with the logging function of the data logger to ensure that within-group variation in incident irradiance is minimized. A mathematics channel on the data logger could be configured to return approximate K_d values for each group of readings. If the approximate K_d values are recorded, large discrepancies between groups at a station could alert field crews to problems. Even at shallow stations, multiple groups of observations (i.e. at 0.5, 1.0 m and at 0.7, 1.2 m) would improve the K_d results obtained by regression.

Sensor cross calibration are being performed, but appear more variable than expected (95% to 120% agreement). Training to develop an awareness of potential reflective or obscuring bodies in making these measurements is suggested. In addition, multiple readings are suggested since the cross calibration value will be applied to all field data.

During post-processing, field PAR should be corrected for changing irradiance before calculation of K_d values and should be adjusted to normalize between sensors based on cross calibration results.

Data entry

Water quality data are presently being entered in the SWFWMD Water Management Information System (WMIS) with a row for each analytical, *in situ*, or calculated value. Required fields identify projects, stations, date time and other information, but PAR data have not previously been included. Unique samples are identified by a combination of date-time-station-depth-replicate to permit samples from multiple depths at a station, and replicate samples to be collected at a single station-depth to assess system homogeneity.

Table 2 presents a suggested abbreviated format for including PAR data with the associated water quality data collected for the Charlotte Harbor monitoring programs. It is proposed to enter computed attenuation coefficients with the same time as station water quality data to permit easy alignment of K_d with color and other parameters. Depth of K_d remains blank as it pertains to the entire measured water column. Due to spectral absorption effects which reduce K_d with increasing depth, calculated Kd becomes a function of the measurement depths. While the maximum and minimum depths used for K_d computation could be included in the characteristic name, to allow for precise work in the future, individual PAR data should also be reported. Sensor cross calibration results could be entered as a fraction, also under the same time.

Parameter or characteristic names for PAR data should carry some identification of the sensor used. (For older data with multiple readings at multiple depths, characteristic name could be "SENSOR 1 of 1" to indicate that only one sensor was used.) Data for PAR fall into three categories; 1) completely raw data which match field logbooks, 2) PAR data which have been adjusted for sensor cross calibration (i.e. one sensor matches logbooks, the other sensor has had the cross calibration factor applied), and 3) cross calibrated PAR data with air corrections applied for changing incident irradiance.

It is suggested that cross calibrated and air-normalized PAR (3) be entered into WMIS as a minimum as these are the data form which K_d values are calculated. Air normalized air readings are not needed as all would equal 2000 $\mu E\ m^{-2}\ s^{-1}$. Access to PAR data (and not just K_d values) will permit more detailed error analysis, removal of outliers, examination of spectral effects with depth, and comparison with optical model results in the future.

If easy traceability to field logbooks is desired, then cross calibrated PAR data (2) should also be entered together with the group air readings. Inclusion of these data will also permit evaluation of variation in incident irradiance. All PAR data should have times that are distinct both from water quality data and unique for the individual groups to permit identification of groups if cross calibrated PAR are reported and for consistency with cross calibrated and air-normalized data.

Table 1. Source of potential errors in PAR measurements. Green=unaffected, light green=some impact, pink=larger impact.

Potential Error Source	Single group of readings for Kd	Correct?	Two or more groups of readings, mean of group Kd values	Correct?	Kd from regression of all PAR and depths (more than 1 group)	Correct?	Probability	Potential Solution
Incorrect calibration factor for air sensor	Unaffected	n/a	Unaffected	n/a	Unaffected	n/a	Low	Training
Incorrect calibration factor for upper or lower sensor, or switching cables on data logger	Affects slope (Kd)	No	Affects slope of each, affects overall average	No	Spread in data, lower correlation, averages out to some degree	No	Low	Training
Bias between upper and lower sensor	Affects slope (Kd)	Yes, post-correct	Affects slope of each, affects overall average	Yes, post-correct	Spread in data, lower correlation, averages out to some degree	Yes, post-correct	High	cross calibrations Laboratory and daily
Recording/transposition of a single submerged PAR value	Affects slope (Kd)	No	One incorrect Kd, offset by others depending on magnitude	Possibly, remove outlier if >2 groups	Spread in data, lower correlation, averages out to some degree	Possibly, remove outlier	Low	Random, n/a
Changing cloud conditions between groups	Unaffected	n/a	Unaffected	n/a	Spread between data pairs if uncorrected	Yes, post-correct	High	Data processing
Changing cloud conditions within a group	Affects slope (Kd)	No	One incorrect Kd, offset by others depending on magnitude	Possibly, remove outlier if >2 groups	Spread in data, lower correlation, averages out to some degree	Possibly, remove outlier	High	Use data logging function
Reflection/shading on air sensor for one group, or recording error of air for one group	Unaffected	n/a	Unaffected	n/a	Spread in data, lower correlation, averages out to some degree	Possibly, remove 2 outliers if >2 groups	Low	Training
Sensor separation not as recorded	Affects slope (Kd)	No	Affects slope of each, affects overall average	No	Spread in data, lower correlation, averages out to some degree	No	Low (higher when separation was variable)	No longer an issue
Depth of upper sensor not as recorded	Unaffected	n/a	Unaffected	n/a	Spread in data, lower correlation	Possibly, remove 2 outliers if >2 groups	Moderate	Training/mark apparatus
Wave focusing on shallowest reading (esp. <0.5 m)	Affects slope (Kd)	No	One incorrect Kd, offset by others depending on magnitude	Possibly, remove outlier if >2 data	Spread in data, lower correlation, averages out to some degree	Possibly, remove outlier	Low	Math channel, extend integration time

Table 2. Proposed data storage format for inclusion in SWFWMS WMIS.

DATE	STATION	TIME	DEPTH	REP	PARAMETER	VALUE	COMMENTS
2/3/2010	038	1123	1.0	0	COLOR	45	These data already stored
2/3/2010	038	1123	2.0	0	COLOR	23	
2/3/2010	038	1123	1.0	0	CHLOROPHYLL	3.6	
2/3/2010	038	1123	1.0	1	CHLOROPHYLL	3.2	
2/3/2010	038	1123	1.0	0	TURBIDITY	4.5	
2/3/2010	038	1123	1.0	0	TKN	1.1	
2/3/2010	038	1123	0.5	0	SALINITY	23.3	
2/3/2010	038	1123	1.0	0	SALINITY	23.5	
2/3/2010	038	1123	-9.0	0	"Kd" or "Kd, 0.5-2.5 m"	0.89	Use time of remaining WQ data so can match with color, etc., this Kd could be the best possible, i.e. w/out outliers
2/3/2010	038	1123	-9.0	0	SENSOR CALIBRATION 1/2	1.16	Optional to store this data
2/3/2010	038	1124	0.5	0	PAR, AIR NORMALIZED, SENSOR 1 of 2	900	Can obtain max and min depth by station from these data for
2/3/2010	038	1124	1.0	0	PAR, AIR NORMALIZED, SENSOR 2 of 2	500	spectral considerations. Data identified as successive groups
2/3/2010	038	1125	1.0	0	PAR, AIR NORMALIZED, SENSOR 1 of 2	550	1 minute apart for each group and at a different time from
2/3/2010	038	1125	1.5	0	PAR, AIR NORMALIZED, SENSOR 2 of 2	300	remaining WQ data. Can compute regression slope with
2/3/2010	038	1126	2.0	0	PAR, AIR NORMALIZED, SENSOR 1 of 2	266	these data or with a Sensor 1 subset, or a single time pair
2/3/2010	038	1126	2.5	0	PAR, AIR NORMALIZED, SENSOR 2 of 2	133	Air readings not needed since all the same
2/3/2010	038	1124	0.0	0	PAR, AIR SENSOR	1000	Data corrected for sensor cross calibration but not for air
2/3/2010	038	1124	0.5	0	PAR, SENSOR 1 of 2	900	readings so can see variation in air readings over the station.
2/3/2010	038	1124	1.0	0	PAR, SENSOR 2 of 2	500	Data identified as successive groups 1 minute apart for each
2/3/2010	038	1125	0.0	0	PAR, AIR SENSOR	2000	group and at a different time from remaining WQ data
2/3/2010	038	1125	1.0	0	PAR, SENSOR 1 of 2	1100	
2/3/2010	038	1125	1.5	0	PAR, SENSOR 2 of 2	600	
2/3/2010	038	1126	0.0	0	PAR, AIR SENSOR	1500	
2/3/2010	038	1126	2.0	0	PAR, SENSOR 1 of 2	400	
2/3/2010	038	1126	2.5	0	PAR, SENSOR 2 of 2	200	

Literature Cited

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