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COMPARTMENT DELINEATION FOR A WETLAND WATER QUALITY MODEL IN THE NORTHERN EVERGLADES, FLORIDA, USA

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A water-quality model application to large geographical areas typically involves the spatial aggregation of sub-areas into compartments which are assumed within the model to be uniform. Model compartments often are delineated using available data and professional judgment. Compartment delineation affects the accuracy of hydrodynamic and water quality modeling by subjectively grouping sub-areas of similar characteristics. In this research, we applied cluster analysis (CA) to objectively determine the number of compartments and to spatially delineate compartments with similar descriptive features for water-quality modeling. Here, surface-water quality data collected in the A.R.M. Loxahatchee National Wildlife Refuge (Refuge), Florida were analyzed using CA of concentrations of chloride, total phosphorus, sulfate, and calcium measured at sites distributed throughout the Refuge. The Refuge is a remnant of the northern Everglades wetland ecosystem encircled by a levee and borrow canal. Cluster analysis classified the marsh into six spatial compartments: Perimeter East; Perimeter West; Transition East; Transition West; Interior North; and Interior South. Although the perimeter canals surrounding the Refuge marsh are all connected, they clustered into three water quality compartments: Canal East; Canal Northwest; and Canal Southwest. Cluster validation criteria (pseudo F statistic and the cubic clustering criterion) indicate that there is an advantage of this new compartmental design when compared with our previous compartmentalization method that delineated boundaries using only distance from the canal to the marsh interior and professional judgment. This new approach provides a more technically rigorous compartmentalization for the purposes of water quality modeling. The approach supports more efficient modeling of spatial and temporal variation in water quality along the gradient from both the peripheral canal to the marsh interior, and from west to east and from north to south gradients.

INTRODUCTION

The Arthur R. Marshall Loxahatchee National Wildlife Refuge (Refuge) is an impounded marsh established in the 1950s for protection of wildlife habitat as well as sources of water supply and flood protection (USFWS, 2007a). Soft-water wetlands were once common in all but coastal regions of the Everglades (USFWS, 2000; McCormick and Harvey, 2007), but today, the interior-most area of the Refuge marsh is the last remaining, large remnant of a soft-water wetland in the Everglades ecosystem. The Refuge also is affected by excessive levels of nutrients including sulfate (Harwell et al., 2008; Wang et al., 2008). An understanding of Refuge water quality in terms of dissolved minerals, nutrients, sulfate, and other constituents, is essential for supporting management decisions on restoring and protecting the Everglades ecosystem (USFWS, 2000). Water quality in the Refuge shows spatial and temporal patterns because of variations in pumped inflow and structure outflow timing, concentration, and location in the perimeter canals, as well as marsh vegetation distribution, bathymetry, rainfall, and evapotranspiration (USFWS, 2000; Arceneaux et al., 2007; USFWS, 2007a,b; Harwell et al., 2008; Surratt et al., 2008). Water and contaminants discharged into the Refuge perimeter canals either flow through the canals to discharge structures, or enter the marsh as overbank flows from the canals (Harwell et al., 2008; Surratt et al., 2008). Water-quality modeling is essential for understanding the complexities of spatial and temporal water-quality patterns.

Two alternatives for implementing large-scale wetland water-quality models involve either: (1) a spatially distributed model, or (2) spatially aggregated (lumped) model defined by a number of compartments that are assumed to each be uniform or well-mixed. One example of a spatially distributed model is the ELM, the Everglades Landscape Model (Fitz and Trimble, 2006); an example of a compartmental (lumped) model is the Refuge Water Quality Model (Arceneaux et al., 2007; Wang et al., 2008). Although spatially distributed models can predict detailed information about spatial variations, they often are limited by the lack of supporting spatial data at modeled resolutions, and by high computational cost. Alternatively, compartmental models can only detect spatial variations among compartments, and are therefore constrained by the initial spatial compartment boundary delineation. In general, compartments should be delineated to minimize water quality variation within each compartment, and preserve important spatial variations between compartments. In this paper, we describe the use of cluster analysis (CA) to improve and quantify the objective delineation of compartment boundaries in support of Refuge water quality model development.

Constituent concentrations are affected by hydrological, geological, topographic, climatic, and biological factors as well as their interaction (Davis, 1994; Boyer and Fourqurean, 1997; Güler et al., 2002; McCormick and Harvey, 2007; USFWS, 2007a, b). For example, increased sulfate loading can lead to the increased release of adsorbed phosphorus into soil pore-water through competition for anion binding sites on peat surface or complexation of Fe to produce Fe-S instead of Fe-P complexes (McCormick and Harvey, 2007). Elevated concentrations of chloride can exert the same competitive binding effect on phosphorus in peat soils (McCormick and Harvey, 2007). Because of these interactions, no single parameter is likely to optimally support compartmental delineation (Güler et al., 2002).

Previously, Arceneaux et al. (2007) divided the Refuge into four compartments in a one-dimensional series arrangement (one canal compartment, and three inner marsh compartments). This compartment delineation was based qualitatively on the distribution of chloride and phosphorus concentrations with distance from the canal. The first marsh compartment was within the first kilometer from the canal (0 - 1 km), the second marsh compartment was between one and four kilometers from the canal (1 - 4 km), and the third marsh compartment aggregated the remaining interior marsh area (> 4 km). Arceneaux et al. (2007) concluded the four-compartment model worked well in explaining field observations. However to improve the model, a more technically rigorous approach was needed for defining compartments to improve the model accuracy. This is because compartment delineation affects the calculation of water flow and constituent transport and the accuracy of hydrodynamic and water quality models. Additionally, the four-compartment model could only describe the canal-marsh gradient, and could not describe two-dimensional spatial gradients in major water-quality parameters. That is, it could not examine spatial variations between eastern and western areas of the Refuge, or variations from north to south.

Cluster analysis (CA) is a statistical procedure that can classify multi-variate data into meaningful groups based on a quantitative measure of similarity when the number of groups and other information about their composition may be unknown. In CA, based on a selected metric that defines distance within the *n*-dimensional space of observed parameters, a cluster is defined as an "aggregate of points such that the distance between any two points in the cluster is less than the distance between any point in the cluster and any point not in it" (Gengerelli, 1963). Cluster analysis provides an objective basis for determining the intrinsic grouping (also called natural clusters) (Banerjee and Dave, 2004), thus, CA is capable of generating a relatively accurate map of water quality zones for water quality compartmental modeling. Cluster analysis has been applied in other wetland water quality studies (e.g., Boyer and Fourqurean, 1997; Güler et al., 2002; Ryberg, 2006). In this research, our objectives were: 1) grouping water quality monitoring sites in the Refuge based on similarities in selected major water quality constituents for the period of 1995-2006 using CA; and, 2) validating and testing the significant difference among groups of the new clustering.

METHODS

Study Area

The Refuge is located in the subtropical region of South Florida (latitude 26º 21.36' to 26º 41.04' N; longitude 80º 13.32' to 80º 26.7' W; Figure 1). Marsh soil topography in the Refuge interior is quite flat, and elevation ranges from approximately 3.2 to 5.6 m (1929 NGVD), and gently declines from north to south (USFWS, 2007a). The Refuge marsh is a mosaic of long-hydroperiod habitats including slough, wet prairie, sawgrass, brush, and cattail (USFWS, 2000). Thousands of mostly small tree islands - slightly elevated areas that support woody vegetation, are a prominent Refuge feature (Brandt et al., 2000; Brandt et al., 2002), and add to the complexity of modeling analysis. The Refuge originally developed as a rainfall-driven system as a part of the contiguous Everglades that is now compartmentalized to meet flood control and water supply (Light and Dineen, 1994; Jordan et al., 1997). Consequently, in the pre-development period, concentrations of nutrients and inorganic ions in Refuge surface water were low (USFWS, 2000; McCormick and Harvey, 2007; Miller and McPherson, 2008). Today, the Refuge marsh is impounded by levees and encircled by a 100-km levee borrow canal with an average width of 40 m. This canal floods or drains the marsh seasonally and in response to rain, inflow, and outflow events in a manner analogous to riverine interaction with flood plain wetlands. Flow into the Refuge occurs originates at inflow pumps, and outflow occurs through gated water control structures. The land use of the upstream drainage basin to the Refuge has changed from natural Everglades marsh

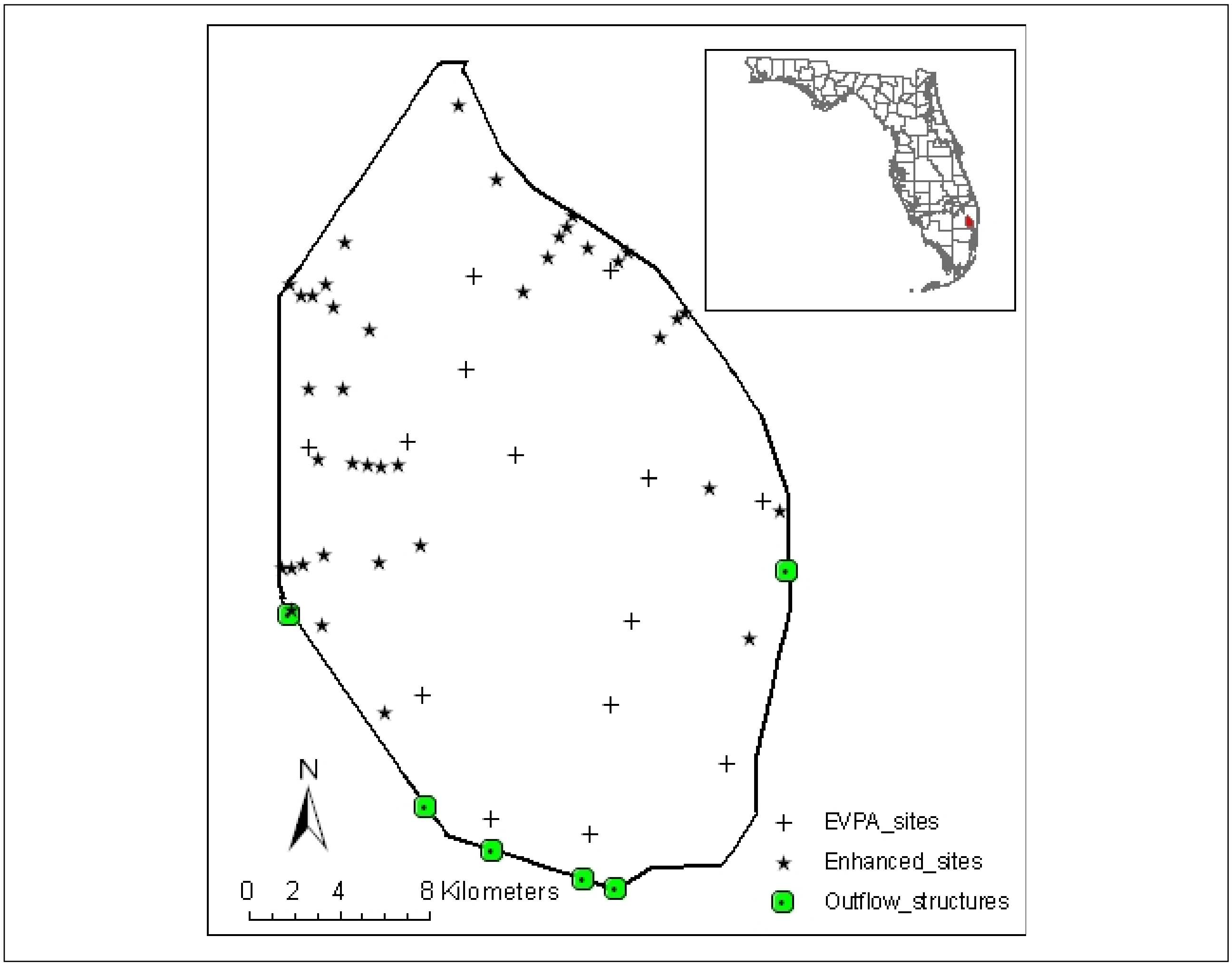

Figure 1. Location of the A.R.M. Loxahatchee National Wildlife Refuge, Florida and distribution of hydraulic structures and water quality monitoring sites in the Refuge. Inset shows the location of the Refuge in Florida.

to agriculture and some urban use resulting in substantially elevated nutrient and mineral concentrations in the inflow, canal, and marsh.

Selection of water quality parameters

The criteria for selecting water quality parameters or constituent concentrations for use in CA included: 1) one constituent to approximate a conservative tracer; 2 non-conservative constituent concentrations coupled to biogeochemical processes; and 3) relative independence among parameters. For clustering water-quality sites and delineating compartments for Refuge water-quality modeling purpose, we selected (in the order of most to least conservative) chloride (Cl), calcium (Ca), sulfate (SO4) and total phosphorus (TP). Chloride was selected because of its common use as a conservative water tracer for hydrodynamic modeling (Arceneaux et al., 2007), and as an indicator of water hardness in the Refuge (Surratt et al., 2008). Calcium was selected as an essential plant nutrient that is linked directly to spatial gradients of periphyton community composition in the Refuge (Moss, 1972; McCormick and Harvey, 2007). Sulfate was chosen as it is an important constituent closely related to soil redox condition and mercury methylation (Orem et al., 2002; Jeremiason et al., 2006; Scheidt and Kalla, 2007; Wang et al., 2008). Finally, TP was chosen as it is the limiting nutrient in the Refuge, is closely related to species distribution (e.g., cattail), and is a well-studied constituent in the Everglades related to ecosystem restoration efforts (Scheidt and Kalla, 2007). Each of these constituent concentrations is elevated in pumped inflows relative to surface water in the less-impacted interior marsh (USFWS, 2007a, b).

Water quality monitoring sites

Data from three water quality monitoring projects with sites distributed over the Refuge marsh and perimeter canals were analyzed: 1) Everglades Protection Area (EVPA) interior marsh sites (14 marsh sites) sampled monthly by the South Florida Water Management District (SFWMD); 2) enhanced monitoring sites in the marsh and perimeter canal (34 marsh sites, 5 canal sites) sampled monthly by the U.S. Fish and Wildlife Service (USFWS); and, 3) permit-related outflow structure monitoring sites within the perimeter canal (6 canal sites) sampled by the SFWMD. Marsh and canal sites were analyzed in separate CA. Water quality data were obtained from the SFWMD's DBHYDRO online database (http://www.sfwmd.gov/org/ema/dbhydro/) and from the USFWS. A small fraction of TP and SO4 values were reported as below the minimum detection level (MDL). In these cases, a value of one-half of the MDL was used in data analyses allowing for comparison with regulatory datasets for the State of Florida (USFWS, 2007a). Only data collected in 1995 or later were used in analysis. Because water quality data among all these sites were not collected on the same date, and the period of record available varied among sites (1995-2006 for EVPA sites and hydraulic structures, 2004-2006 for enhanced sites), we used the 25^{th}, 50^{th} (median), and 75^{th} percentile of the raw data for Cl, Ca, SO4, and TP for CA. These percentiles correspond to the general interpretation (low, moderate and high concentrations) of a site for each water quality parameter in the marsh and canal.

Cluster Analysis

Clusters identified through CA often are highly sensitive to the variables used, and inclusion of highly correlated variables can dramatically affect cluster analysis results (e.g., Güler et al., 2002). We used a de-correlation method (Conrads et al., 2003) for water quality parameters because Ca and SO4 are closely related to Cl. De-correlation is accomplished by generating regression equations for Ca to Cl and SO4 to Cl, then removing the information contained in the Cl signal from the Ca and SO4 signals by computing the residuals (subtracting the predicted Ca and SO4 values from actual Ca and SO4 measurements). The regression residuals for Ca and SO4 were used in the analysis. We also used geographic site coordinates (northing and easting in UTM meters) in the CA to incorporate the additional modeling objective of defining spatially contiguous and compact clusters. Similarity measures (distance metrics) used in CA can be highly sensitive to differing scales among variables. In this case, coordinate values in meters exceed constituent concentrations in mg/L by orders of magnitude. Variables were therefore standardized to have equal weight (mean = zero and standard deviation = 1) before conducting CA. Results of CA often are sensitive to the distance metric selected. A Euclidean metric (straight line distance between two points in p-dimensional space defined by n variables), and Ward's method for linkage (Güler et al., 2002), were used here, as this combination was found to produce the most distinctive groups.

In CA, water quality sites are grouped into clusters in a repeated process that builds a hierarchical cluster tree (a dendrogram). Selection of a cut-off distance then determines the best number of clusters. This selection, termed cluster validation (Banerjee and Dave, 2004), identifies partitioning with well-isolated and coherent clusters while keeping the number of clusters small. Three criteria were applied here in cluster validation: the cubic clustering criterion (CCC), a pseudo F statistic (PSF); and a pseudo t^2 statistic (Milligan and Cooper, 1985). The rule of thumb for identifying the break point for not increasing the number of clusters is to look for consensus among the three statistics, that is, local peaks of the CCC and PSF combined with a small PST2 and a larger PST2 in the next cluster level in the order of large to small number of clusters (SAS Institute Inc., 2004).

The statistical package for CA and other statistical analysis was SAS 9.1.3 (http://www.sas.com). PROC CLUSTER in SAS was used in implementing the agglomerative hierarchical clustering algorithm. Based on these statistically defined clusters of sites, a map of Refuge water quality zones was drawn, and the area of each zone in the marsh and canal was calculated using ArcGIS 9.0 (http://www.esri.com). These geographic zones can be defined as compartments of Refuge hydrodynamic and water quality models because each zone has similar water quality characteristics and influences from canal water.

Comparison of the two Refuge compartmentalization methods

CA seeks to minimize within-group variance and maximize between-group variance. Therefore, a one-way ANOVA F value that is the ratio of between-group variation to within-group variation was used as the criterion to determine if CA would produce a more statistically sound classification of Refuge water quality compartments compared to the earlier compartmental design of Arceneaux et al. (2007). A large F value indicates that the variation between classification groups is much larger than the variation within classification groups, thus a better classification. PROC GLM in SAS was used to compute F values with water quality group as the only one independent variable and water-quality parameters as response variables. In addition to the 25th, 50th, and 75th percentiles, the 5th, 10th, 90th and 95th percentiles of the available raw data of Cl, Ca, SO4 and TP also were used in this comparison to provide a broader data range for comparison. The minimum and maximum values of the raw data were not included because these values are more likely to be affected by outliers, and because minimum levels often are simply representative of the MDL.

Significant test of the differences between paired compartments

The same dataset (5th, 10th, 25th, 50th, 75th, 90th and 95th percentiles of the raw data of Cl, Ca, SO4 and TP) was used for statistically testing differences among clustered water quality compartments. A nonparametric test was used because the data were not normally distributed. PROC NPAR1WAY in SAS was used to perform the significant test of the differences using the Kruskal-Wallis rank sum test between each paired water-quality zones in the marsh and the rim canal for Cl, Ca, SO4 and TP and (SAS Institute Inc., 2004; Ryberg, 2006).

RESULTS

Water quality compartments in the Refuge

The numbers of compartments identified through CA for the marsh and the rim canal are six and three, respectively, based on the values of PSF and CCC (Table 1). The proportions of total variance, as indicated by the coefficient of determination (R^2) accounted for by the marsh and canal clustering are 73% and 69%, respectively (Table 1). The six marsh areas in the Refuge were: Perimeter East, Perimeter West, Transition East, Transition West, Interior North, and Interior South. The three rim canal compartments were termed: Canal East, Canal Northwest, and Canal Southwest (Figure 2). Based on our boundary delineations from CA (Figure 2), the percentage of each compartment of the total marsh area was calculated using ArcGIS (Table 2). Approximately 79% of the marsh occurs in the two most interior marsh compartments - 38% in Interior North, and 41% in Interior South. Less than 15 % of the marsh is located in narrow transition

Table 1. Cluster validation for water quality sites in the A.R.M. Loxahatchee National Wildlife Refuge. The number of clusters selected for the marsh and canal network are shown in bold.

Area	NCL	CCC	PSF	PST2	R^2
Marsh	9	37.9	20.6	6.4	0.81
	8	37.3	20.6	9.8	0.78
	7	37.4	21.1	2.7	0.76
	6	38.2	22.2	3.9	0.73
	5	34.2	20.3	6.7	0.65
	4	31.2	19.4	20.4	0.57
	3	27.2	18.6	7.2	0.45
	2	18.1	16.2	8.4	0.26
Canal	4	na	11.4	9.0	0.83
	3	na	9.0	7.2	0.69
	2	1.92	5.7	7.6	0.39

Note: NCL= number of clusters; CCC = cubic clustering criterion; PSF = pseudo F statistic; PST2 = pseudo t^2 statistic; R^2 = coefficient of determination; na = not available.

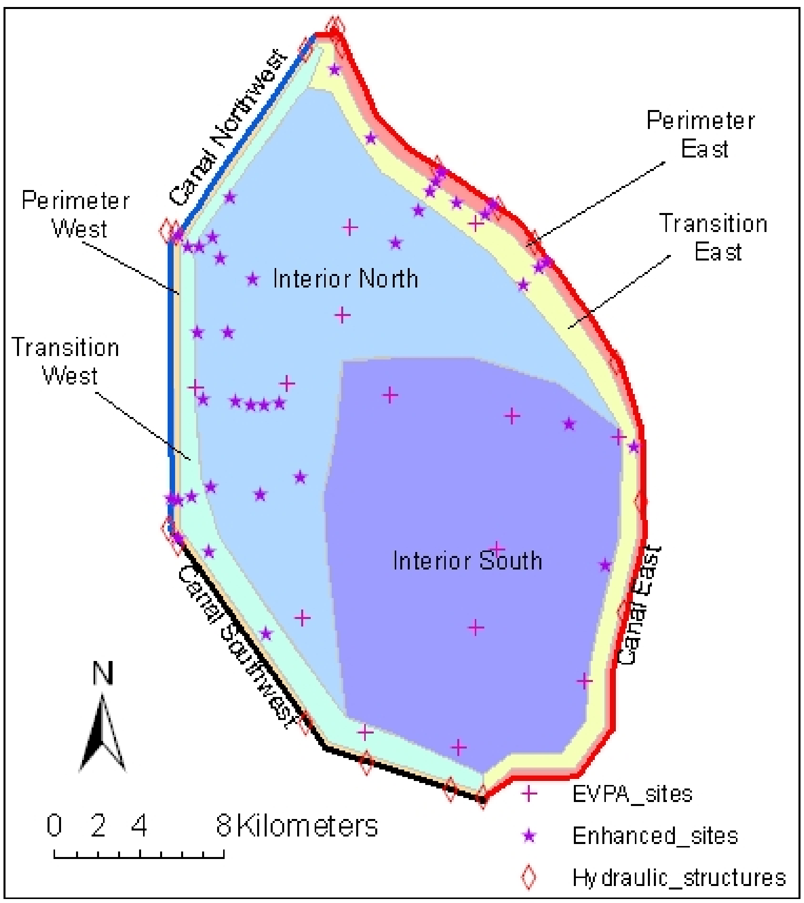

Figure 2. Map of water quality compartments defined by cluster analysis in the A.R.M. Loxahatchee National Wildlife Refuge, Florida. Canal width is exaggerated in this figure for clarity.

compartments, and less than 6% of the marsh is located in the narrow perimeter compartments (Table 2).

Comparison with the previous Refuge compartmentalization method

The CA-based division method had higher *F* values for Cl, Ca, SO4 and TP for the Refuge marsh compared to the compartmentalization by Arceneaux et al. (2007) (Table 3). These high values indicated that grouping by CA produced the largest between-group variance and/or the smallest within-group variance. Marsh grouping by CA was highly significant ($p<0.01$) for all four parameters, whereas the compartmentalization by Arceneaux et al. (2007) was not significant for Cl, SO4 and TP, and significant at a lower level for Ca ($p<0.05$).

Table 2. Water quality compartments defined by cluster analysis in the A.R.M. Loxahatchee National Wildlife Refuge.

Description	Sites	Area (ha)	% of Total Area
Marsh:			
Perimeter West	A121	1,324	2.4
Perimeter East	A133, A136	2,038	3.6
Transition East	A101, A126, A130, A131, A134, A137, A140, Lox4	4,187	7.5
Transition West	A105, A116, A117, A122, A123, Lox15	4,151	7.4
Interior North	A102, A103, A106, A107, A108, A109, A110, A111	21,355	38.2
	A112, A113, A114, A118, A119, A120, A128, A138		
	A139, Lox3, Lox5, Lox9, Lox10, Lox12		
Interior South	A124, A127, Lox6, Lox7, Lox8, Lox11, Lox13	22,925	40.9
	Lox14, Lox16		
Canal:			
East	A129, A132, A135, G94B	202	50.1
Northwest	A104, A115	112	27.8
Southwest	S-39, S-10A, S-10C, S-10D, S-10E	89	22.1

Table 3. Comparison of the two compartmentalization methods for modeling the A.R.M. National Wildlife Refuge using the ANOVA *F* statistic.

Division Methods	# of compartments	Parameter	F value	Pr > F	F value	Pr > F
			Marsh		Canal	
Cluster Analysis	6 marsh, 3 canal	Cl	4.5	0.0028**	0.9953	0.3891
(this study)		Ca	10.88	0.0001**	0.4429	0.649
		SO4	6.04	0.0004**	1.6391	0.2218
		TP	5.11	0.0012**	0.7434	0.4895
1-D distant from canal	3 marsh, 1 canal	Cl	2.89	0.0814		
by Cl and TP		Ca	4.57	0.0249*		
(Arceneaux et al., 2007)		SO4	2.28	0.1315		
		TP	1.68	0.2145		

Significant test of paired water quality compartments

Significant differences for individual water quality constituents were found between paired compartments (Table 4). For Cl, the Perimeter West and Perimeter East compartments were significantly different from both Interior North and Interior South compartments, while the Transition East and Transition West compartments were significantly different from the Interior South compartment. For Ca, the Perimeter West compartment was significantly different from all compartments except the Perimeter East, while the Perimeter East, Transition East and Transition West compartments were significantly different from the North and South Interior compartments. For SO4, the Perimeter West compartment was significantly different from all compartments except the Transition West. The Perimeter East and Transition East compartments were significantly different from the Interior South compartment. The Transition West compartment was significantly different from the Interior North and Interior South compartments. For TP, the Perimeter West compartment was significantly different from all compartments except the Perimeter East. The Perimeter East compartment also was significantly different from the transition and interior

Table 4. *P*-values for Kruskal-Wallis test of significant differences between paired compartments in the marsh areas of the A.R.M. Loxahatchee National Wildlife Refuge.

Parameter	Zone	M2	M3	M4	M5	M6
CL	M1	0.1797	0.1102	0.1417	0.0088**	0.0027**
	M2		0.4822	0.848	0.0476*	0.0088**
	M3			0.848	0.845	0.035*
	M4				0.845	0.0476*
	M5					0.4062
CA	M1	0.1797	0.0127*	0.0476*	0.0017**	0.0017**
	M2		0.1594	0.3379	0.006**	0.0017**
	M3			0.848	0.035*	0.0127*
	M4				0.0476*	0.0151*
	M5					0.7494
SO4	M1	0.035*	0.0127*	0.0845	0.004**	0.0017**
	M2		0.4822	0.3379	0.1102	0.0253*
	M3			0.2774	0.1797	0.0476*
	M4				0.035*	0.0088**
	M5					0.5224
TP	M1	0.4057	0.004**	0.004**	0.0017**	0.0017**
	M2		0.0252*	0.0252*	0.0058**	0.004**
	M3			0.6081	0.4042	0.3358
	M4				0.7005	0.7483
	M5					0.9488

Note: M1 = Perimeter West; M2=Perimeter East; M3=Transition East; M4=Transition West; M5=Interior North; and M6=Interior South.
**: very significant (p<0.01); *: significant (p<0.05).

compartments. No significant difference between transition and interior compartments was found for TP.

On the western side, the perimeter and transition compartments were significantly different for Ca and TP; on the eastern side, perimeter and transition compartments were significantly different for TP. The two perimeter compartments were significantly different for SO4 (Table 3). There were no significant differences between Interior North and Interior South compartments for any of the four water quality parameters (Table 4). There are no statistically significant differences between the paired canal compartments.

DISCUSSION

Water quality-based compartmentalization of the Refuge using the CA method was reasonable and helpful in developing improved Refuge water-quality model simulations. A narrow perimeter compartment (0 - 300 m from the canal on the western side and 0 - 600 m from the canal on the eastern side) and a narrow transition compartment (~300 - 1300 m from the canal on the western side and ~600 - 1600 m from the canal on the eastern side) near the rim canal were identified for Refuge marsh areas by the CA method. This marsh compartmentalization reflects influences of topographic variations, vegetation, and soil properties on canal water inflow and constituents transport in the Refuge.

The Perimeter West and Perimeter East compartments are represented by only one and two sampling stations (Table 2). A cluster containing only one station (singleton) might be an indication of an outlier arise normally from measurements in cluster analysis (e.g., SAS Institute Inc., 2004). However, no measurement errors were found for these three stations (A121, A133 and A136). It is the nature of water quality data that classify these stations into different clusters. For example, on the western side, the Perimeter West compartment is significantly different from the Transition West compartment in CA and TP (Table 4). The fact that there are few monitoring sites in the two perimeter compartments suggests that additional sites are needed within these perimeter compartments to examine the substantial changes in water quality parameters and affecting factors.

The identification of narrow zones along the canals is consistent with previous studies that document narrow marsh areas near the rim canal that are more variable in hydrology and more impacted in water quality. Marsh areas near the canals are associated with elevated concentrations of constituents (Surratt et al., 2008) and establishment of monotypic cattail communities (Childers et al., 2003). Canal-induced local groundwater recharge is highest within roughly 600 m of canals across the Everglades landscape, and this 600-m zone represents a critical area controlling the local water budget (Krest and Harvey, 2003; Harvey et al., 2004). The statistical differentiation of eastern and western perimeter and transition compartments may result from the western marsh having been more impacted by canal water intrusion than the eastern marsh because larger volumes of inflows have been discharged into the western canal (USFWS, 2007 a, b) with, at times, higher concentrations of mineral and nutrient constituents (USFWS, 2007a, b), or subtle topological differences.

For modeling purposes, a large area of the Refuge marsh was classified into two marsh interior compartments. This classification may be indicative that water quality in the large marsh interior is influenced by natural factors such as rainfall, and existence of a more uniform mixing with canal water. The separation of Interior North from Interior South by the CA method, although not significant for Cl, Ca, SO4 and TP by statistical test, may be due to the north-to-south soil elevation gradient and resulting sheet flow (McCormick and Harvey, 2007). Additionally, the identification of three canal compartments by CA, although not significant for the four parameters, indicated that water quality tends to vary along the canal. Nevertheless, it should be noted that statistically significant differences should not be expected for all paired compartments defined by CA for all water quality parameters, but the differences do provide insight into processes that will be modeled.

The identified compartments are qualitatively consistent with the distribution of the major vegetation types and soil properties (Corstanje et al., 2006). For example, monotypic cattail is the dominant macrophyte community in perimeter compartments. Correspondence of these water quality-based compartments with major vegetation types is not only supportive of the credibility of the CA methodology, but additionally should be beneficial in hydrodynamic modeling because of the importance of vegetative resistance in controlling flow (Kadlec, 1990; Voinov et al., 1998) and the significant correlation between vegetation types (e.g., slough, wet prairie, and sawgrass) and water depth, an important metric of hydroperiod in the Everglades (Jordan et al., 1997). Vegetation type also plays an important role in determining phosphorus settling rate (e.g., plant phosphorus uptake and retention) in phosphorus modeling (e.g., Davis, 1994; Kadlec and Knight, 1996).

CONCLUSIONS

Although the CA approach certainly does not replace the need for modeling judgment, the CA approach does provide an objective, reproducible and defensible basis supporting the determination of both the appropriate number and the delineation of model compartments. Cluster analysis successfully supported the delineation of compartments with most similar water quality characteristics, and this Refuge compartmentalization can be used for lumped hydrodynamic and water quality modeling. The fact that there are few monitoring sites in the two perimeter compartments where substantial changes in water quality parameters tend to occur demonstrates that monitoring would be more supportive of model development if additional sites were established within these perimeter compartments. Our approach of identifying compartments for wetland hydrological and water quality modeling could be applied to modeling studies of other wetlands, particularly those that are impacted by flood flows from adjacent water-bodies.

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REFERENCES

Arceneaux, J.C., E.A. Meselhe, and M.G. Waldon. 2007. The Arthur R. Marshall Loxahatchee National Wildlife Refuge water budget and water quality models. U.S. Fish and Wildlife Service Open-File Report LOXA-07-004.

Banerjee, A., and R.N. Dave. 2004. Validating clusters using the Hopkins statistic. In Proceedings of IEEE International Conference on Fuzzy systems (FUZZ-IEEE 2004), Budapest, Hungary, July 2004, pp. 149-153.

Boyer, J.N., and J.W. Fourqurean. 1997. Spatial characterization of water quality in Florida Bay and Whitewater Bay by multivariate analyses: zones of similar influence. Estuaries, Vol. 20, pp. 743-758.

Brandt, L.A., K.M. Portier, and W.M. Kitchens. 2000. Patterns of change in tree islands in Arthur R. Marshall Loxahatchee National Wildlife Refuge from 1950 to 1991. Wetlands, Vol. 20, pp. 1-14.

Brandt, L.A., J.E. Silveira, and W.M. Kitchens. 2002. Tree Islands of the Arthur R. Marshall Loxahatchee National Wildlife Refuge. P. 311-335. In F.H. Sklar and A. van der Valk (ed.) Tree Islands of the Everglades. Kluwer Academic Publishers.

Childers, D.L., R.F. Doren, R. Jones, G.B. Noe, M. Rugge, and L.J. Scinto. 2003. Decadal change in vegetation and soil phosphorus pattern across the Everglades landscape. Journal of Environmental Quality, Vol. 32, pp. 344-362.

Conrads, P.A., E.A. Roehl, and W.B. Martello. 2003. Development of an empirical model of a complex, tidally affected river using artificial neural networks. National TMDL Science and Policy 2003 Specialty Conference. Water Environment Federation.

Corstanje, R., S. Grunwald, K.R. Reddy, T.Z. Osborne, and S. Newman. 2006. Assessment of the spatial distribution of soil properties in a Northern Everglades Marsh. Journal of Environmental Quality, Vol. 35, pp. 938-949.

Davis, S.M.. 1994. Phosphorus inputs and vegetation sensitivity in the Everglades. pp. 357-378. In S.M. Davis and J.C. Ogden (ed.) Everglades: The Ecosystem and its Restoration. St. Lucie Press, Delray Beach, Florida.

Fitz, H.C., and B. Trimble. 2006. Documentation of the Everglades Landscape Model: ELM v2.5. South Florida Water Management District. http://my.sfwmd.gov/elm Reviewed by independent expert panel, reported at http://my.sfwmd.gov/elm.

Gengerelli, J.A. 1963. A method for detecting subgroups in a population and specifying their membership. Journal of Psychology, Vol. 55, pp. 457-68.

Güler, C., G.D. Thyne, J.E. McCray, and K. Tuner. 2002. Evaluation of graphical and multivariate statistical methods for classification of water chemistry data. Hydrogeology Journal, Vol. 10, pp. 455-474.

Harvey, J.W., S.L. Krupa, and J.M. Krest. 2004. Ground water recharge and discharge in the Central Everglades. Ground Water, Vol. 42, pp. 1090-1102.

Harwell, M.C., D.D. Surratt, D.M. Barone, and N.G. Aumen. 2008 Conductivity as a tracer of agricultural and urban runoff to delineate water quality impacts in the northern Everglades. Environmental Monitoring and Assessment, DOI 10.1007/s10661-007-0131-3.

Jeremiason, J.D., D.R. Engstrom, E.B. Swain, E.A. Nater, B.M. Johnson, J.E. Almendinger, B.A. Monson, and R.K. Kolka. 2006. Sulfate Addition Increases Methylmercury Production in an Experimental Wetland. Environmental Science and Technology, Vol. 40, pp. 3800-3806.

Jordan, F., H.L. Jelks, and W.M. Kitchens. 1997. Habitat structure and plant community composition in a Northern Everglades wetland landscape. Wetlands, Vol. 17, pp. 275-283.

Kadlec, R.H. 1990. Overland flow in wetlands: vegetation resistance. Journal of Hydraulic Engineering, Vol. 116, pp. 691-706.

Kadlec, R.H., and R.L. Knight. 1996. Treatment Wetlands. Lewis Publishers, January 1996, Boca Raton, Florida.

Krest, J.M., and J.W. Harvey. 2003. Using natural distributions of short-lived radium isotopes to quantify groundwater discharge and recharge. Limnology and Oceanography, Vol. 48, pp. 290-298.

Light, S.S., and J.W. Dineen. 1994. Water Control in the Everglades: a historical perspective. In S.M. Davis and J.C. Ogden (ed.) Everglades: The Ecosystem and its Restoration. St. Lucie Press, Delray Beach, Florida.

McCormick, P.V., and J.W. Harvey. 2007. Influence of changing water sources and mineral chemistry on the Everglades Ecosystem [Online]. U. S. Geological Survey, Administrative Report. Reston, VA. Available at http://water.usgs.gov/nrp/sheetflow/publications.html.

Miller, R.L., and B.F. McPherson. 2008. Water quality in the Arthur R. Marshall Loxahatchee National Wildlife Refuge—trends and spatial characteristics of selected constituents, 1974-2004. USGS Scientific Investigations Report 2007-5277. 34 p. http://pubs.usgs.gov/sir/2007/5277/.

Milligan, G.W., and M.C. Cooper. 1985. An examination of procedures for determining the number of clusters in a data set. Psychometrika, Vol. 50, pp. 159 - 179.

Moss, B. 1972. The influence of environmental factors on the distribution of freshwater algae: An experimental study: I. Introduction and the influence of calcium concentration. Journal of Ecology. Vol. 60, pp. 917-932.

Orem, W., H. Lerch, A. Bates, M. Corum, and M. Beck. 2002. Sulfur contamination and geochemistry of the Everglades [Online]. USGS Open-File Report 03-54. Available at http://sofia.usgs.gov/publications/ofr/03-54/.

Ryberg, K.R.. 2006. Cluster analysis of water-quality data for Lake Sakakawea, Audubon Lake, and McClusky Canal, Central North Dakota, 1990-2003: U.S. Geological Survey Scientific Investigations Report 2006-5202, 38 p.

SAS Institute Inc. 2004. SAS OnlineDoc® 9.1.3. Cary, NC: SAS Institute Inc.

Scheidt, D.J., and P.I. Kalla. 2007. Everglades ecosystem assessment: water management and quality, eutrophication, mercury contamination, soils and habitat: monitoring for adaptive management: a R-EMAP status report. USEPA Region 4, Athens, GA. EPA 904-R-07-001. 98 pp.

Surratt, D.D., M.G. Waldon, M.C. Harwell, and N.G. Aumen. 2008. Time-series and spatial tracking of polluted canal water intrusion into wetlands of a national wildlife refuge in Florida, USA. Wetlands, Vol. 28, pp. 176-183.

USFWS. 2000. Arthur R. Marshall Loxahatchee National Wildlife Refuge Comprehensive Conservation Plan [Online]. US Fish and Wildlife Service, Boynton Beach, FL. Available at http://loxahatchee.fws.gov.

USFWS. 2007a. A.R.M. Loxahatchee National Wildlife Refuge - Enhanced Monitoring and Modeling Program – 2nd Annual Report – February 2007 [Online]. LOXA06-008, U.S. Fish and Wildlife Service, Boynton Beach, FL. 183 pp. Available at http://sofia.usgs.gov/lox_monitor_model/reports/2nd_annual_07.html.

USFWS. 2007b. A.R.M. Loxahatchee National Wildlife Refuge - Enhanced Water Quality Monitoring and Modeling Program – 3rd Annual Report – October 2007. LOXA07-005, U.S. Fish and Wildlife Service, Boynton Beach, FL. 116 pp. Available at http://sofia.usgs.gov/lox_monitor_model/reports/3rd_annual_07.html.

Voinov, A.A., H.C. Fitz, and R. Costanza. 1998. Surface water flow in landscape models: 1. Everglades case study. Ecological Modeling, Vol. 108, pp. 131-144.

Wang, H., M.G. Waldon, E.A. Meselhe, J. C. Arceneaux, C. Chen, and M. C. Harwell. 2008. Surface water sulfate dynamics in the northern Florida Everglades, USA. Journal of Environmental Quality. (in press).

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