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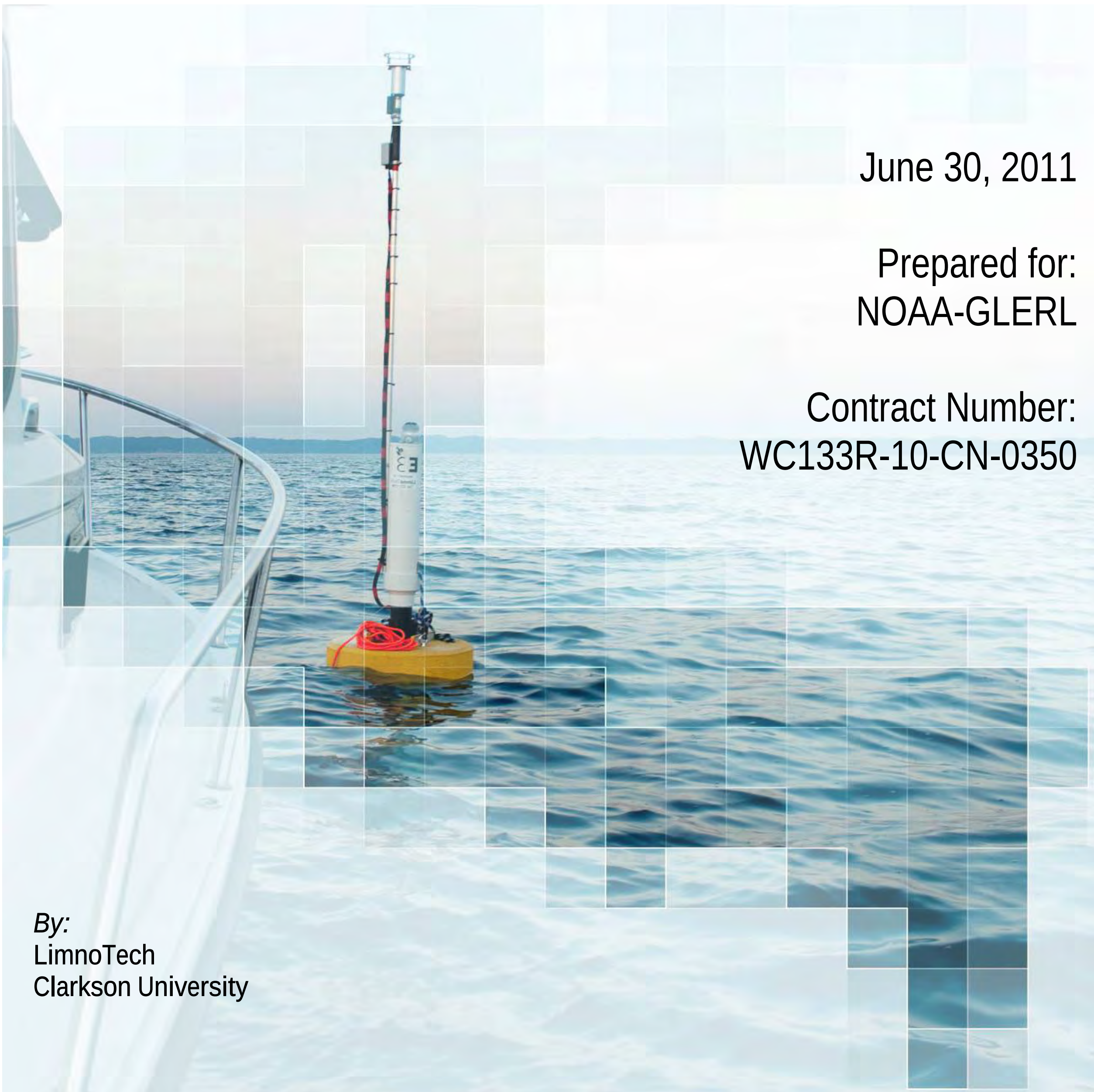
TRADE STUDIES

Near-Term Design of the Great Lakes Observing System Enterprise Architecture



June 30, 2011

Prepared for:
NOAA-GLERL

Contract Number:
WC133R-10-CN-0350

By:
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Clarkson University

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Great Lakes Observing System
Enterprise Architecture
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1. INTRODUCTION

Trade studies are systematic and transparent decision-making tools that allow for the comparison of competing design alternatives. In its Systems Engineering Manual, the National Airspace System (NAS, 2006) describes trade studies as a process for selecting a balanced solution that meets project requirements in a cost-effective manner. The trade study approach tends to prevent commitment to an early design that may not be the optimum solution. The Systems Engineering Manual recommends an approach that includes the following components, which were incorporated into the trade studies presented in this document:

- Determine scope and methodology;
- Select or develop alternative solutions;
- Determine evaluation criteria and weighting factors;
- Evaluate alternatives;
- Review results and develop conclusions; and
- Document the process and results.

For the development of the GLOS enterprise architecture, trade studies were used to evaluate the mix of observing platforms that would be most appropriate for the expansion of the GLOS sensing network. The project team used trade studies to demonstrate a process that will facilitate the design of future sensing networks. The trade studies were applied as follows:

- A single trade iteration was performed for each example design area described in Section 6 of the design document to illustrate how the preferred observing platform mix could vary based on scale and design management issues.
- Two iterations of the trade studies were applied to each of the end-to-end case studies to demonstrate how the trade study process can move from general guidance to a comparison of specific observing network alternatives.

This appendix describes the trade study process, presents the results of the trade studies performed as part of this investigation, and provides a brief user guide for the application of the trade study tool for future design efforts.

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2. DESCRIPTION OF TRADES

A critical, over-arching factor affecting the design of the GLOS-EA is scale. Scale affects the technical performance of the sensing system, the management requirements of the system, the funding mechanisms that support the system, and the political environment in which the system exists. Consequently, a decision was made early in the project definition phase to segment the design effort into three different scales of consideration that are convenient for focusing the design and the addressing the user needs that the system serves: basin-wide, lake-wide, and regional. Example design areas at each scale are presented in the design report. The trade studies were conducted for observing system expansion alternatives for each example design area:

- The Great Lakes Basin
- Lake Michigan considering multiple management issues
- Lake Michigan only addressing trophic gradients
- The central basin of Lake Erie
- The western basin of Lake Erie

For each design area, a series of management issues were identified that would potentially drive the design of an observing system. The parameters measured by an observing system that would address those management issues were also identified. Additionally, a summary of the existing sensing network relevant to meeting the identified user needs was generated.

The following is a brief summary of the management issues to be addressed by the sensing network, the parameters to be measured, and existing observing infrastructure identified for each area:

Basin-wide Scale

<u>Great Lakes Basin</u>

Management issues: The basin-wide system addresses nearly all of the management issues identified in the design report, but does not meet all of their data needs.

Parameters to be measured: Focus on physical issues such as water levels, wave heights, ice cover, and basin-wide hydrology.

Existing monitoring:

- Buoys deployed by NOAA Great Lakes Environmental Research Laboratory (GLERL), National Data Buoy Center (NDBC), and the Great Lakes Observing System (GLOS)
- National Weather Service (NWS) stations
- Canadian Weather Office stations
- USGS stream gauges and monitoring sites
- NOAA water level stations

- 2009 Canada Water Act Long-Term Sites
- Canadian Aquatic Biomonitoring Network
- Canada Clean Air Regulatory Act monitoring stations
- Integrated Atmospheric Deposition Network (IADN)
- EPA and State of the Lakes Ecosystem Conference (SOLEC) research vessel monitoring
- Satellites
- Current imagery -MODIS, MERIS, Landsat, AVHRR, aerial, commercial high-resolution
- Products - NOAA Coastwatch
- Partial high-resolution bathymetry from the USACE and NOAA
- Canadian Great Lakes Shoreline Photos
- National Ice Center (NIC) forecasts

Lake-wide Scale

<u>Lake Michigan (multiple management issues)</u>

Management issues:

- Nearshore wetlands loss
- Nearshore/offshore trophic gradients
- Persistent Toxic Substances effects and management
- Shoreline protection

Parameters to be measured:

- Wind speed and direction
- Wave height and currents
- Bathymetry
- Total Suspended Solids (TSS)
- Light regime
- Nutrients (phosphorus, nitrogen, silica forms)
- Chlorophyll
- Biota (phytoplankton, zooplankton, cladophora, dreissenids)
- Water temperature
- Toxics (e.g, PCDD/Fs, PCBs, PAHs, PCDDs, pesticides) in multiple media
- Total organic carbon
- Wetland and shoreline delineation

Existing monitoring:

- Observations listed in basin-wide existing monitoring
- GLERL RECON buoys
- University of Wisconsin, Milwaukee Pioneer and Endurance buoys

- University of Michigan: Marine Hydraulics Laboratory – Upper Great Lakes Observing System (UGLOS) buoys
- Monitoring by various state agencies and academic institutions (including recent efforts by the National Monitoring Network (NMN))
- USGS continuous monitoring of 20 Lake Michigan tributaries
- Autonomous Underwater Vehicle deployment in Green Bay and Milwaukee (NMN)
- Regular EPA-GLNPO ship monitoring in spring and fall
- Lake Michigan SOLEC and Cooperative Science and Monitoring Initiative monitoring

Lake-wide Scale

<u>Lake Michigan (single management issues)</u>

Management issues:

- Nearshore/offshore trophic gradients

Parameters to be measured:

- Light regime
- Nutrients (phosphorus, nitrogen, silica forms)
- Chlorophyll
- Biota (phytoplankton, zooplankton, cladophora, dreissenids)
- Temperature

Current monitoring:

- Same as the those listed above for Lake Michigan

Regional Scale

<u>Central Basin of Lake Erie</u>

Management issues:

- Hypoxic intrusion in the Cleveland drinking water system

Parameters to be measured:

- Dissolved oxygen, conductivity, pH, and water temperature at multiple depths
- Meteorological parameters (air temperature, relative humidity, barometric pressure, wind speed and direction)

Current monitoring:

- Observations listed in basin-wide existing monitoring
- GLERL RECON buoy
- University monitoring (OSU Sandusky)
- Rivermouth monitoring (GLOS/NOAA)

<u>Maumee River and Bay</u>

Management issues:

- Sedimentation
- Hazardous algal blooms

Parameters to be measured:

- Wind and waves
- Air and water temperature
- TSS, volatile suspended solids, and particle size distribution
- Chloride
- Light regime
- Nutrients (phosphorus, nitrogen, silica forms)
- Chlorophyll and phycocyanin
- Microcystin
- Biota (phytoplankton (species), , zooplankton, Lyngbya, Dreissenids)

Current monitoring:

- Observations listed in basin-wide existing monitoring
- GLERL RECON buoys
- NOAA GLERL Hazardous Algal Bloom monitoring
- University Monitoring (Heidelberg, University of Toledo, Bowling Green, Ohio State University)

For each design area, the trade studies were used to evaluate the most appropriate category of observing technology emphasis: fixed platforms, mobile platforms, field campaigns, or remote sensing. Fixed technologies are geographically fixed measurements including sensors attached to buoys and platforms. Mobile sensing includes tow-bodies and Autonomous Underwater Vehicles (AUVs). Field campaigns are traditional monitoring techniques that utilize grab sampling, and normally involve laboratory analysis. Remote sensing is the interpretation of satellite or airborne imagery to provide data, as well as technologies such as HF Radar. An observing system at any scale is likely to include all four components. The overall configuration within the scale of observation will be a mix of the four components with differing emphasis depending on which technology or platform scores highest and which scores lowest.

2.1 OBSERVING PLATFORM ALTERNATIVES

Three forms of in-situ measurements (fixed platforms, mobile platforms, and field campaigns) plus remote sensing were evaluated as part of each trade study. The observing platform alternatives are described below.

2.1.1 Fixed Platforms

Fixed platforms use sensors placed in the same location for the duration of sampling or deployment. The types of observation technologies evaluated in the category of fixed platforms include:

- Long-term moorings (surface, sub-surface)
- Buoy systems
- Cabled systems
- Vertical profiling systems

Surface long-term moorings lend themselves to flexibility, ease of maintenance and deployment within the observing system. Sub-surface moorings require more stringent design considerations and specialized maintenance support, however, they allow for year round monitoring. Buoy systems are the workhorse of observing systems and are relatively easier to support. For longer term observations, cabled systems might be desirable and can support larger payloads and more specialized equipment. Vertical profilers are either surface or sub-surface units that provide the capability to profile the entire water column for a variety of parameters.

2.1.2 Mobile Platforms

Mobile platforms utilize similar sensors, and therefore can measure similar parameters, as fixed platforms. However, mobile platforms provide greater spatial resolution, but less temporal resolution at individual locations. Typical components of this category include:

- Tow-bodies
- Autonomous underwater vehicles (AUVs)
- Gliders
- Drifters
- Vessels of opportunity

Tow-bodies are capable of undulating through the water column generating a vertical profile while the vessel is underway, providing a moderate resolution dataset at relatively high sampling frequency. AUVs also undulate through the water, however they are independent of a parent vessel for support and can be deployed as a fleet to provide higher spatial resolution. They typically support short duration sampling experiments. Gliders have similar characteristics to AUVs, but can support longer term deployments. Drifters are comparable to buoys but are free to drift with the currents and do not possess active controls. Vessels of opportunity are not dedicated observing system platforms, but are regular water craft that have volunteered to carry instrument payloads. The Ranger III, a ferry to Isle Royale in Lake Superior, is an example of a vessel of opportunity in the Great Lakes.

2.1.3 Field Campaigns

Field campaigns are traditional sampling techniques which rely heavily on grab sampling. For many parameters, particularly biological measurements, field campaigns are still the only feasible monitoring method. Research vessels and any sample procurement that uses laboratory analysis are included in this category.

2.1.4 Remote Sensing

Remote sensing relies on non-contact sensing methods. Typical remote sensing platforms are:

- Satellite based systems
- Aerial platforms (aircraft, balloons, sondes)

- Land-based (radar, infrared)

Remote platforms provide extensive coverage but may be limited in terms of spatial resolution and sampling frequency. A variety of free satellite imagery is available; however, the imagery requires processing to provide useful products. Land-based radar units such as high frequency (HF) radar provide surface current mapping but may not have enough coverage in fresh water systems. Infrared sensors can provide sea surface temperature mapping. For higher sampling frequency, aerial platforms can provide sufficient coverage relative to satellite overpasses but cost of deployment may become a limiting factor.

2.2 OBJECTIVE CRITERIA

As described in the design document, the study team developed a series of design drivers that would guide decision-making for the GLOS-EA. Those design drivers are:

- User need focus/management decision making support
- Model-centrality
- Build-out flexibility
- Funding flexibility
- Sensing technology flexibility
- Support to the Great Lakes research community
- Support to the operational user community
- Need for interoperability of systems across scales
- Bi-national focus
- Recognition and preservation of extensive in-place sensing systems
- Need for interoperability of systems across Great Lakes regions
- Need for standardization of data sharing and storage protocols, and metadata standards

Using the design drivers as a starting point, the project team identified specific criteria that would assist in the evaluation of the ability of observing technologies to address defined management issues. The team identified 12 criteria categories and 40 individual criteria by which to evaluate the observing platform alternatives. The criteria fell into two broad categories: those that measured a characteristic intrinsic to the technology for a particular scale (e.g., system reliability and data quality) and those that measured a characteristic that varied depending on the management issue being addressed (e.g., provides adequate temporal resolution). The technologies that measured a characteristic that varied based on the management issue were generally given higher criteria weights, which are discussed later in this section. Table 1 shows the criteria categories and the individual criteria used in the trade studies.

Table 1. Criteria categories and individual criteria used to evaluate observing platform technologies

Criteria Category	Criteria
Platform Intrinsic Criteria (for Scale of Application)	
Functional requirements	Does not need further analyses / post-processing
	Supports year round sampling
Operational requirements	Ease of deployment
	Flexibility
	Scalability
Technical risk	Reliability
	Maintainability
	Availability
	System Safety
	Data Quality
	Human Factors
	Environmental Impact
	Hazardous Materials
System maturity	System maturity
Support	Developmental support
	Logistics support
	Engineering support
	Testing support
	Ease of data integration
Management Issue Dependent Criteria	
Functional requirements	Ability to measure relevant parameters
	Ability to provide appropriate sensor placement
Performance requirements	Provides adequate spatial coverage
	Provides adequate spatial resolution
	Provides adequate temporal resolution (sampling frequency)
Programmatic requirements	Ability to address design issue
	Ability to address other user needs (IOOS, GLRI, etc.)
Cost	Development cost
	Lifecycle cost
Financial opportunity	Amenable to steady funding (federal, state, etc.)
	Amenable to opportunistic funding
Schedule risk	Long-term schedule risk
	Medium-term schedule risk
	Short-term schedule risk
Operations	Amenable to internal operations
	Amenable to external operations
	Amenable to opportunistic sampling
Ownership	Suitability for academic ownership
	Suitability for federal ownership
	Suitability for state/local ownership
	Suitability for private-party ownership

Weights were assigned to the each of the criteria to represent their relative importance to the successful design of a sensing network. Initial criteria weights were determined through a survey of the study team. These initial weights were generally applied in each trade; however, some of the criteria weights were adjusted based on the management issue that was being addressed. For example, providing adequate spatial coverage was given greater weight for the basin-wide system than for the central basin of Lake Erie.

2.3 SCORING THE ALTERNATIVES

Each alternative was given a score from 0-10 to reflect its performance with regard to each of the criteria. The scoring of the criteria was oriented so that a higher score always indicated better performance. For example, a higher score in the cost criteria indicated a lower cost. For this study, the scores were based on expertise of the members of the GLOS-EA team. A survey was conducted to gather initial scores from each organization with experience deploying and operating the various observing platforms: LimnoTech, Clarkson, and MTRI. In the cases in which the initial scores from the different groups were fairly close, the average value rounded to the nearest integer was used as the score for that alternative. The criteria that had more disparate initial score responses were discussed further to develop consensus-based scores.

The individual scores were multiplied by the criteria weights to calculate a Total Score for each alternative. The Total Score is calculated for each alternative based on the following equation:

$$TS_j = \sum_{i=j=1}^{n} w_i r_j$$

where w_i is the weight for each criterion and r_j is the score for each alternative. A spreadsheet based tool was developed to calculate criteria score, criteria category score, and Total Score for each alternative. The matrices of scores and weights used to develop a Total Score for each trade are presented in Tables 8 through 14 at the end of this Appendix.

3. TRADE STUDY RESULTS

3.1 FIRST ITERATION TRADES

A single iteration of a trade study was completed for each design area. The Total Scores for each broad observing platform category are presented in Table 2.

Table 2. First iteration Total Scores from trade studies for each example design area

Example Design Area	Fixed Platforms	Field Campaigns	Mobile Platforms	Remote Sensing
Basin-wide design area				
Great Lakes Basin	481	423	437	516
Lake-wide design area				
Lake Michigan (multiple user needs)	521	560	534	568
Lake Michigan (trophic gradient)	469	494	459	466
Basin-wide design area				
Central basin of Lake Erie	569	495	517	425
Maumee River and Bay	562	534	536	548

Note: A trade study was conducted for a Lake Michigan sensing network that addresses multiple user needs as defined in the RDA presented in Section 6 of the design report. Additionally, a trade study was conducted to develop a design for the Lake Michigan end-to-end case study which only addresses the issue of the nearshore-offshore trophic gradient.

The single iteration trade studies show that the appropriate observing platform mix is highly dependent on both the scale of application and the management issues that the observing system is intended to address. The fixed platforms tend to be the preferred technology at the regional scale, while remote sensing tends to be more valuable at larger scales. The mobile platforms and field campaigns generally score in the range that indicates they should serve as complimentary observing system components. However, some management issues, such as the nearshore/offshore primary productivity gradient, are still best monitored with parameters that can only be measured with field campaigns.

3.2 SECOND ITERATION TRADES

A single iteration trade study will provide only very general guidance regarding the appropriate sensing network design direction. Further iterations are needed to develop and evaluate more specific design alternatives. To illustrate this process, second iteration trade studies were performed for each of the end-to-end case studies.

For the central basin of Lake Erie, the first iteration trade study showed that fixed platforms were the preferred observing technology. Therefore, fixed platforms were the primary technology in each of the alternatives developed for a second iteration. Conversely, remote sensing scored low for the central basin example design area, primarily because it does not measure dissolved oxygen and it cannot provide depth profiling. Remote sensing was not considered as a component in the second iteration alternatives. Field campaigns and mobile platforms both scored well enough to be considered as complimentary observing technologies. Importantly, field campaigns and mobile platforms both scored well in providing spatial resolution and spatial coverage, two areas of relative weakness for fixed platforms.

Three design alternatives of approximately equal cost were developed based on the outcome of the first iteration trade study. The alternatives are presented in Table 3 along with the scores from the second iteration trade study.

Table 3. Second iteration alternatives from trade studies central basin of Lake Erie end-to-end case study

Alternative	Fixed platforms	Field campaigns	Mobile platforms
Fixed platforms only	• 6 buoys to measure DO, conductivity, pH, and water temperature at several depths • 1 of the 6 buoys will also measure air temperature, relative humidity, barometric pressure, wind speed and direction • Sensors at 4 drinking water intakes to measure DO, temperature, conductivity, pH, color, and turbidity		
Fixed platforms supplemented with field campaigns	• 5 buoys to measure DO, conductivity, pH, and water temperature at several depths • 1 of the 5 buoys will also measure air temperature, relative humidity, barometric pressure, wind speed and direction • Sensors at 4 drinking water intakes to measure DO, temperature, conductivity, pH, color, and turbidity	• Field cruises every two weeks from mid-June to mid-August to obtain water quality profiles. Probe lowered every mile to measure temperature, DO, conductivity, and pH. At select locations, grab samples will be collected to measure TP, TN, silica and chlorophyll.	
Fixed platforms supplemented with mobile platforms	• 4 buoys to measure DO, conductivity, pH, and water temperature at several depths • 1 buoy to also measure air temperature, relative humidity, barometric pressure, wind speed and direction • Sensors at 4 drinking water intakes to measure DO, temperature, conductivity, pH, color, and turbidity		• AUV deployment every two weeks from mid-June to mid-August to obtain water quality profiles. Sensors to measure temperature, conductivity, DO, and pH.

Table 4. Second iteration Total Scores from trade studies for central basin of Lake Erie end-to-end case study

Design Issue and Area	Fixed platforms only	Fixed platforms supplemented with field campaigns	Fixed platforms supplemented with mobile platforms
Hypoxic intrusion in drinking water intakes in the central basin of Lake Erie	569	581	567

The results from the second iteration trade study indicate that, of the alternatives evaluated, the preferred alternative is the one using five buoys, sensors at the drinking water intakes, and semi-monthly field campaigns. These results were used to inform the central basin of Lake Erie design described in the Section 6.4.2.b of the design report.

The first iteration trade study for the Lake Michigan trophic gradient end-to-end case study indicated that a balance of sensing technologies was needed, but that field campaigns should be a substantial component. Three alternative configurations were developed. All of the alternatives included additional fixed platforms to inform the hydrodynamic model, field campaigns to measure parameters that cannot currently be measured with sensors, and the development of new remote sensing algorithms to measure cladophora, chlorophyll, total suspended solids (TSS), and dissolved organic matter (DOM). From that base level of sensing, the alternatives were expanded in three directions: increased emphasis on field sampling, increased emphasis on fixed platforms, and increased emphasis on remote sensing. Table 5 provides the details about the three alternatives considered in the second iteration trade study.

Table 5. Second iteration alternatives from trade studies for Lake Michigan end-to-end case study

Alternative	Fixed platforms	Field campaigns	Mobile platforms	Remote sensing
Emphasis on Field Campaigns	• 8 buoys to measure meteorological data, currents, and water temperature. 4 with multi- parameter sonde*. • 1 cabled year-round platform to measure water temperature, waves, current, and ice cover	• 10 research vessel cruises along 6 transects to buoys with measurements for nutrients, phytoplankton and zooplankton biomass and speciation, and benthic algae and organism abundance	• Tow-bodies deployed as part of field campaigns to measure , Chl-a, turbidity, PAR, conductivity, DOM, temperature, DO, side-scan sonar and lake-bottom video • 2 multi-day glider deployment with same sensor payload as towed arrays	• Analysis for cladophora, chlorophyll, TSS, and DOM using existing free satellite imagery
Emphasis on Fixed Platforms	• 15 buoys to measure meteorological data, currents, and water temperature. 9 with multi- parameter sonde*. • 2 cabled year-round platforms to measure water temperature, waves, current, ice cover	• 6 research vessel cruises along 6 transects to buoys with measurements for nutrients, phytoplankton and zooplankton biomass, and benthic algae and organism abundance	• Tow-bodies deployed as part of field campaigns to measure , Chl-a, turbidity, PAR, conductivity, DOM, temperature, DO, side-scan sonar and lake-bottom video • 2 multi-day glider deployments with same sensor payload as towed arrays	• Analysis for cladophora, chlorophyll, TSS, and DOM using existing free satellite imagery
Emphasis on Remote Sensing	• 8 buoys to measure meteorological data, currents, and water temperature. 4 with multi- parameter sonde*. • 1 cabled year-round platform to measure water temperature, waves, current, and ice cover	• 6 research vessel cruises along 6 transects to buoys with measurements for nutrients, phytoplankton and zooplankton biomass, and benthic algae and organism abundance	• Tow-bodies deployed as part of field campaigns to measure , Chl-a, turbidity, PAR, conductivity, DOM, temperature, DO, side-scan sonar and lake-bottom video • 2 multi-day glider deployment with same sensor payload as towed arrays	• Analysis for cladophora, chlorophyll, TSS, and DOM using high resolution satellite or airborne imagery

The second iteration alternatives were evaluated with the trade study tool. The Total Scores are presented in Table 6.

Table 6. Second iteration Total Scores from trade studies for Lake Michigan end-to-end case study

Design Issue and Area	Emphasis on Field Campaigns	Emphasis on Fixed Platforms	Emphasis on Remote Sensing
Nearshore/offshore trophic gradients	519	498	500

The results from the second iteration trade study are consistent with the first iteration in that they indicate that field campaigns should be an area of emphasis for addressing the trophic gradients in Lake Michigan. However, the process of developing specific alternatives revealed that additional fixed platforms were needed to inform a hydrodynamic model. The investment in the base level of fixed platforms would be greater than the field campaigns, even in the alternative that emphasized additional field sampling. This illustrates how the trade study process can change as the design considerations become better-specified.

Trade studies are useful as a systematic approach to decision-making; however, they should only be regarded as a framework to guide the design. The need to meet specific design considerations, such as measuring particular model inputs, may supersede the results of a group-based decision-making process. This is particularly true for high-level design decisions, such as the first iteration trade studies, when the specific design objectives and alternatives may not be well defined and the trade-offs among technologies may be poorly constrained.

An additional tool that may inform the appropriate sensing network design is an Observing System Simulation Experiment (OSSE). OSSEs can help identify the specific information needs that are most likely to reduce uncertainty in the predictions of operational models. The application of OSSEs is well-established within NOAA and NASA (Masutani et al, 2006). For the GLOS, the use of OSSEs would be most appropriate for improving the performance physical models such as the Great Lakes Forecasting System.

4. TRADE STUDY USER GUIDE

This section provides a brief user guide for the application of the trades study tool developed as part of the GLOS enterprise architecture design.

1) Define management issues and data needs that will guide design
   The management issues that the observing system is intended to inform should drive the design. The management issues will determine the parameters that will be measured, the frequency of measurements that are needed, and the spatial coverage and resolution that the sensing network should provide. The ability to meet these data needs is a major component of how the alternatives are scored. Better defined data needs will lead to trade studies that better evaluate potential design alternatives.

2) Inventory existing observing infrastructure
   As part of the development of the GLOS enterprise architecture, an inventory of the existing basin-wide observing infrastructure has largely been completed (described in the design report and Technical Memorandum 3). However, for most regional sub-areas, additional information will be available that has not been comprehensively catalogued. Creating an inventory of the available information is an important step to perform prior to conducting detailed design of additional sensing networks.

3) Develop alternatives
   The process of developing design alternatives should be an iterative one. Trade studies are useful for guiding even high-level design considerations, such as whether to emphasize in situ monitoring or remote sensing. However, such high-level alternatives can be difficult to score because the design is poorly constrained. The high-level guidance should be used to form more specific alternatives that include number, locations, and configurations of sensors. Specific alternatives can be more easily and accurately scored in terms of cost, performance, and risk criteria.

4) Review criteria and criteria weights for relevance to specific application

   The criteria and weights applied the example trade studies presented in this document may not be appropriate for other applications. For example, a trade study could be applied to determine the appropriate management strategy for an already deployed sensor network. In that instance the criteria and weights could be revised to emphasize cost, risk, and management related criteria. The sensor performance criteria could be de-emphasized or eliminated.

To assist in both criteria weighting and criteria scoring, the following table provides definitions of select criteria which may not be clear from the name alone.

Table 7. Definitions of select criteria.

Operational Requirements	
System flexibility	Ability of an alternative to adjust in response to shifting programmatic interests.
System scalability	Ability of an alternative to be scaled up to address network expansion.
Technical Risk	
Reliability	Assessment of likelihood of system failures relative to system uptime. When possible, this should be based on past performance data.
Maintainability	Assessment of the effort required to keep the alternative operating (high effort = low score).
Availability	Assessment of the overall system uptime with minimum scheduled maintenance.
System safety	Assessment the risk of personnel injury or public safety during course of normal operation
Data quality	Assessment of data quality in terms of accuracy and precision
Human factors	Assessment of the alternatives susceptibility to operator error
Environmental Impact	Assessment of whether the sensing network itself has the potential to negatively impact the environment (high impact = low score)
System Maturity	
System Maturity	Assessment of the level of technological development of a given alternative
Support	
Developmental	Assessment of the level of available support for the development of an alternative relative to the level of support needed
Logistics	Assessment of the level of available logistics support relative to the support needed to configure the network to perform stated goals and objectives
Engineering	Assessment of the availability of the technical support to keep the system fully operational over the long term
Testing	Assessment of the support available to perform technology integration and system upgrades

5) <u>Score the alternatives</u>

The scoring process should be objective whenever possible. Quantitative estimates of factors such as costs should be generated. Inverse modeling, such as Observing System Simulation Experiments, may be useful in generating objective scores for performance criteria. However, scoring for many of the criteria will necessarily be subjective. However, it is important that the scoring process remains systematic and transparent and that multiple opinions are incorporated into the subjective scores.

Two general approaches to scoring subjective criteria could be utilized:

- Surveying a group of subject-matter experts and using a mean or median score
- Forming consensus-based scores from group discussion

The trade studies described in this document utilized a hybrid approach to scoring. In cases where survey-based scores were consistent, a mean value was used. In case where survey-based scores were divergent, further discussion was conducted to examine the reasons for the divergent scores and to develop consensus-based scores.

6) <u>Refine design</u>

As noted in step 3, the design process and application of trade studies should be iterative. The preferred alternative or alternatives from one application of trade studies should be used to generate new alternatives, which are designed to address identified weaknesses. The new alternatives should then be re-evaluated. Using an iterative approach allows weak alternatives to be eliminated and greater effort be directed toward the most promising alternatives. Additionally, it prevents early commitment to a design that may not yet be optimized.

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Table 8. First iteration Trade Study for central basin of Lake Erie.

			Fixed Platforms		Field Campaigns		Mobile Platforms		Remote Sensing	
Criteria	Sub-criteria	Criteria Ranking (0-6)	Raw Score (0-10)	Weighted Score	Raw Score (0-10)	Weighted Score	Raw Score (0-10)	Weighted Score	Raw Score (0-10)	Weighted Score
Platform intrinsic criteria										
Functional Requirements				7		7		8		3
	Does not need further analyses / post-processing	1	7	7	7	7	8	8	3	3
	Supports year round sampling	1	5	5	3	3	4	4	6	6
Operational Requirements				17		15		18		15
	Ease of deployment	1	7	7	4	4	6	6	7	7
	Flexibility	1	5	5	7	7	7	7	3	3
	Scalability	1	5	5	4	4	5	5	5	5
Technical risk (higher scores=lower risk)				90		89		83		97
	Reliability	3	7	21	7	21	7	21	7	21
	Maintainability	1	7	7	8	8	7	7	9	9
	Availability	1	8	8	6	6	6	6	9	9
	System Safety	1	8	8	9	9	7	7	10	10
	Quality (QA/QC)	3	8	24	9	27	7	21	7	21
	Human Factors	1	8	8	5	5	6	6	8	8
	Environmental Impact (high score = low impact)	1	7	7	6	6	8	8	10	10
	Hazardous Materials (high score = low use of haz. materials)	1	7	7	7	7	7	7	9	9
System maturity				24		30		18		15
	System maturity	3	8	24	10	30	6	18	5	15
Support				33		30		28		28
	Developmental support	1	7	7	8	8	5	5	5	5
	Logistics support	1	6	6	5	5	5	5	8	8
	Engineering support	1	6	6	6	6	5	5	6	6
	Testing support	1	6	6	7	7	6	6	5	5
	Ease of data integration	1	8	8	4	4	7	7	4	4
		Sub Total		176		174		159		164
Management issue dependent criteria										
Functional requirements				77		72		81		22
	Ability to measure relevant parameters	5	9	45	8	40	9	45	2	10
	Ability to provide appropriate sensor placement	4	8	32	8	32	9	36	3	12
Performance Requirements				75		49		68		41
	Provides adequate spatial coverage	3	5	15	6	18	8	24	4	12
	Provides adequate spatial resolution	3	5	15	7	21	8	24	3	9
	Provides adequate temporal resolution (sampling frequency)	5	9	45	2	10	4	20	4	20
Programmatic Requirements				70		60		66		36
	Ability to address design issue (nearshore/offshore gradients)	6	9	54	7	42	8	48	3	18
	Ability to address other user needs (IOOS, GLRI, etc.)	2	8	16	9	18	9	18	9	18
Cost (higher scores = lower cost)				56		38		43		61
	Development cost (higher score = lower cost)	3	7	21	6	18	6	18	7	21
	Lifecycle cost (higher score = lower cost)	5	7	35	4	20	5	25	8	40
Financial opportunity				34		32		26		32
	Amenable to steady funding (federal, state etc.)	2	9	18	8	16	7	14	9	18
	Amenable to opportunistic funding	2	8	16	8	16	6	12	7	14
Schedule risk (higher scores=lower risk)				30		25		24		29
	Long-term schedule risk (higher score = lower risk)	1	8	8	8	8	6	6	9	9
	Medium-term schedule risk (higher score = lower risk)	1	8	8	7	7	6	6	8	8
	Short-term schedule risk (higher score = lower risk)	2	7	14	5	10	6	12	6	12
Operations				20		19		22		18
	Amenable to internal operations	1	7	7	5	5	7	7	6	6
	Amenable to external operations	1	8	8	6	6	7	7	6	6
	Amenable to opportunistic sampling	1	5	5	8	8	8	8	6	6
Ownership				31		26		28		22
	Suitability for academic ownership	1	7	7	6	6	7	7	4	4
	Suitability for federal ownership	1	9	9	8	8	8	8	9	9
	Suitability for state/local ownership?	1	7	7	6	6	6	6	4	4
	Suitability for private-party ownership	1	8	8	6	6	7	7	5	5
		Sub Total		393		321		358		261
		Grand Total		569		495		517		425

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Table 9. First iteration Trade Study for the Maumee River and Maumee Bay

			Fixed Platforms		Field Campaigns		Mobile Platforms		Remote Sensing	
Criteria	Sub-criteria	Criteria Ranking (0-6)	Raw Score (0-10)	Weighted Score	Raw Score (0-10)	Weighted Score	Raw Score (0-10)	Weighted Score	Raw Score (0-10)	Weighted Score
Platform intrinsic criteria										
Functional Requirements				12		10		12		9
	Does not need further analyses / post-processing	1	7	7	7	7	8	8	3	3
	Supports year round sampling	1	5	5	3	3	4	4	6	6
Operational Requirements				17		15		18		15
	Ease of deployment	1	7	7	4	4	6	6	7	7
	Flexibility	1	5	5	7	7	7	7	3	3
	Scalability	1	5	5	4	4	5	5	5	5
Technical risk (higher scores=lower risk)				90		89		83		97
	Reliability	3	7	21	7	21	7	21	7	21
	Maintainability	1	7	7	8	8	7	7	9	9
	Availability	1	8	8	6	6	6	6	9	9
	System Safety	1	8	8	9	9	7	7	10	10
	Quality (QA/QC)	3	8	24	9	27	7	21	7	21
	Human Factors	1	8	8	5	5	6	6	8	8
	Environmental Impact (high score = low impact)	1	7	7	6	6	8	8	10	10
	Hazardous Materials (high score = low use of haz. materials)	1	7	7	7	7	7	7	9	9
System maturity				24		30		18		15
	System maturity	3	8	24	10	30	6	18	5	15
Support				33		30		28		28
	Developmental support	1	7	7	8	8	5	5	5	5
	Logistics support	1	6	6	5	5	5	5	8	8
	Engineering support	1	6	6	6	6	5	5	6	6
	Testing support	1	6	6	7	7	6	6	5	5
	Ease of data integration	1	8	8	4	4	7	7	4	4
		Sub-total		176		174		159		164
Management issue dependent criteria										
Functional requirements				64		68		72		63
	Ability to measure relevant parameters	5	8	40	8	40	8	40	7	35
	Ability to provide appropriate sensor placement	4	6	24	7	28	8	32	7	28
Performance Requirements				70		53		66		72
	Provides adequate spatial coverage	2	5	10	5	10	6	12	9	18
	Provides adequate spatial resolution	3	5	15	6	18	8	24	8	24
	Provides adequate temporal resolution (sampling frequency)	5	9	45	5	25	6	30	6	30
Programmatic Requirements				91		86		91		91
	Ability to address design issue (sedimentation)	5	8	40	5	25	8	40	8	40
	Ability to address design issue (hazardous algal blooms)	5	7	35	9	45	7	35	7	35
	Ability to address other user needs (IOOS, GLRI, etc.)	2	8	16	8	16	8	16	8	16
Cost (higher scores = lower cost)				51		44		41		52
	Development cost (higher score = lower cost)	3	7	21	8	24	7	21	4	12
	Lifecycle cost (higher score = lower cost)	5	6	30	4	20	4	20	8	40
Financial opportunity				30		34		28		34
	Amenable to steady funding (federal, state etc.)	2	8	16	9	18	7	14	9	18
	Amenable to opportunistic funding	2	7	14	8	16	7	14	8	16
Schedule risk (higher scores=lower risk)				26		27		26		28
	Long-term schedule risk (higher score = lower risk)	1	7	7	8	8	7	7	8	8
	Medium-term schedule risk (higher score = lower risk)	1	7	7	7	7	7	7	8	8
	Short-term schedule risk (higher score = lower risk)	2	6	12	6	12	6	12	6	12
Operations				22		21		22		22
	Amenable to internal operations	1	8	8	7	7	8	8	7	7
	Amenable to external operations	1	8	8	7	7	7	7	8	8
	Amenable to opportunistic sampling	1	6	6	7	7	7	7	7	7
Ownership				32		27		31		22
	Suitability for academic ownership	1	8	8	5	5	8	8	5	5
	Suitability for federal ownership	1	9	9	9	9	9	9	8	8
	Suitability for state/local ownership?	1	8	8	8	8	7	7	4	4
	Suitability for private-party ownership	1	7	7	5	5	7	7	5	5
		Sub-total		386		360		377		384
		Grand Total		562		534		536		548

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Table 10. First iteration Trade Study for Lake Michigan for multiple management issues.

			Fixed Platforms		Field Campaigns		Mobile Platforms		Remote Sensing	
Criteria	Sub-criteria	Criteria Ranking (0-6)	Raw Score (0-10)	Weighted Score	Raw Score (0-10)	Weighted Score	Raw Score (0-10)	Weighted Score	Raw Score (0-10)	Weighted Score
Platform intrinsic criteria										
Functional Requirements				11		9		10		11
	Does not need further analyses / post-processing	1	5	5	5	5	5	5	3	3
	Supports year round sampling	1	6	6	4	4	5	5	8	8
Operational Requirements				17		19		20		20
	Ease of deployment	1	7	7	6	6	6	6	9	9
	Flexibility	1	5	5	7	7	7	7	4	4
	Scalability	1	5	5	6	6	7	7	7	7
Technical risk (higher scores=lower risk)				91		84		78		95
	Reliability	3	7	21	7	21	6	18	8	24
	Maintainability	1	7	7	6	6	6	6	8	8
	Availability	1	8	8	5	5	6	6	6	6
	System Safety	1	8	8	6	6	7	7	9	9
	Quality (QA/QC)	3	8	24	9	27	7	21	7	21
	Human Factors	1	7	7	6	6	5	5	7	7
	Environmental Impact (high score => low impact)	1	8	8	6	6	7	7	10	10
	Hazardous Materials (high score => low use of haz. materials)	1	8	8	7	7	8	8	10	10
System maturity				24		27		18		18
	System maturity	3	8	24	9	27	6	18	6	18
Support				39		31		30		32
	Developmental support	1	8	8	8	8	6	6	5	5
	Logistics support	1	8	8	6	6	6	6	9	9
	Engineering support	1	8	8	7	7	5	5	7	7
	Testing support	1	7	7	6	6	6	6	5	5
	Ease of data integration	1	8	8	4	4	7	7	6	6
		Sub Total		182		170		156		176
Management issue dependent criteria										
Functional requirements				46		73		67		53
	Ability to measure relevant parameters	5	6	30	9	45	7	35	5	25
	Ability to provide appropriate sensor placement	4	4	16	7	28	8	32	7	28
Performance Requirements				48		51		63		75
	Provides adequate spatial coverage	3	3	9	5	15	6	18	9	27
	Provides adequate spatial resolution	3	4	12	6	18	8	24	8	24
	Provides adequate temporal resolution (sampling frequency)	3	9	27	6	18	7	21	8	24
Programmatic Requirements				88		112		104		116
	Ability to address nearshore wetland loss	4	3	12	4	16	4	16	7	28
	Ability to address productivity gradients	4	7	28	9	36	8	32	6	24
	Ability to address toxics	4	4	16	9	36	4	16	4	16
	Ability to address shoreline protection	4	4	16	2	8	6	24	8	32
	Ability to address other user needs (IOOS, GLRI, etc.)	2	8	16	8	16	8	16	8	16
Cost (higher scores = lower cost)				51		40		38		52
	Development cost (higher score = lower cost)	3	7	21	5	15	6	18	4	12
	Lifecycle cost (higher score = lower cost)	5	6	30	5	25	4	20	8	40
Financial opportunity				30		34		28		34
	Amenable to steady funding (federal, state etc.)	2	8	16	9	18	7	14	9	18
	Amenable to opportunistic funding	2	7	14	8	16	7	14	8	16
Schedule risk (higher scores=lower risk)				26		27		24		28
	Long-term schedule risk (higher score = lower risk)	1	7	7	8	8	6	6	8	8
	Medium-term schedule risk (higher score = lower risk)	1	7	7	7	7	6	6	8	8
	Short-term schedule risk (higher score = lower risk)	2	6	12	6	12	6	12	6	12
Operations				22		21		22		22
	Amenable to internal operations	1	8	8	7	7	8	8	7	7
	Amenable to external operations	1	8	8	7	7	7	7	8	8
	Amenable to opportunistic sampling	1	6	6	7	7	7	7	7	7
Ownership				32		28		29		24
	Suitability for academic ownership	1	8	8	6	6	7	7	5	5
	Suitability for federal ownership	1	9	9	9	9	8	8	10	10
	Suitability for state/local ownership?	1	8	8	8	8	7	7	4	4
	Suitability for private-party ownership	1	7	7	5	5	7	7	5	5
		Sub-total		343		386		375		404
		Grand Total		521		560		534		568

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Table 11. First iteration Trade Study for Lake Michigan end-to-end case study to address trophic gradients.

			Fixed Platforms		Field Campaigns		Mobile Platforms		Remote Sensing	
Criteria	Sub-criteria	Criteria Ranking (0-6)	Raw Score (0-10)	Weighted Score	Raw Score (0-10)	Weighted Score	Raw Score (0-10)	Weighted Score	Raw Score (0-10)	Weighted Score
Platform intrinsic criteria										
Functional Requirements				11		9		10		11
	Does not need further analyses / post-processing	1	5	5	5	5	5	5	3	3
	Supports year round sampling	1	6	6	4	4	5	5	8	8
Operational Requirements				17		19		20		20
	Ease of deployment	1	7	7	6	6	6	6	9	9
	Flexibility	1	5	5	7	7	7	7	4	4
	Scalability	1	5	5	6	6	7	7	7	7
Technical risk (higher scores=lower risk)				91		84		78		95
	Reliability	3	7	21	7	21	6	18	8	24
	Maintainability	1	7	7	6	6	6	6	8	8
	Availability	1	8	8	5	5	6	6	6	6
	System Safety	1	8	8	6	6	7	7	9	9
	Quality (QA/QC)	3	8	24	9	27	7	21	7	21
	Human Factors	1	7	7	6	6	5	5	7	7
	Environmental Impact (high score = low impact)	1	8	8	6	6	7	7	10	10
	Hazardous Materials (high score = low use of haz. materials)	1	8	8	7	7	8	8	10	10
System maturity				24		27		18		18
	System maturity	3	8	24	9	27	6	18	6	18
Support				39		31		30		32
	Developmental support	1	8	8	8	8	6	6	5	5
	Logistics support	1	8	8	6	6	6	6	9	9
	Engineering support	1	8	8	7	7	5	5	7	7
	Testing support	1	7	7	6	6	6	6	5	5
	Ease of data integration	1	8	8	4	4	7	7	6	6
		Sub Total		182		170		156		176
Management issue dependent criteria										
Functional requirements				43		61		54		35
	Ability to measure relevant parameters	5	5	25	8	40	6	30	4	20
	Ability to provide appropriate sensor placement	3	6	18	7	21	8	24	5	15
Performance Requirements				56		60		68		63
	Provides adequate spatial coverage	3	4	12	6	18	6	18	7	21
	Provides adequate spatial resolution	5	4	20	6	30	7	35	6	30
	Provides adequate temporal resolution (sampling frequency)	3	8	24	4	12	5	15	4	12
Programmatic Requirements				50		62		56		44
	Ability to address productivity gradients	6	6	36	8	48	7	42	5	30
	Ability to address other user needs (IOOS, GLRI, etc.)	2	7	14	7	14	7	14	7	14
Cost (higher scores = lower cost)				43		46		37		55
	Development cost (higher score = lower cost)	3	6	18	7	21	4	12	5	15
	Lifecycle cost (higher score = lower cost)	5	5	25	5	25	5	25	8	40
Financial opportunity				26		30		24		30
	Amenable to steady funding (federal, state etc.)	2	7	14	8	16	6	12	8	16
	Amenable to opportunistic funding	2	6	12	7	14	6	12	7	14
Schedule risk (higher scores=lower risk)				22		23		20		24
	Long-term schedule risk (higher score = lower risk)	1	6	6	7	7	5	5	7	7
	Medium-term schedule risk (higher score = lower risk)	1	6	6	6	6	5	5	7	7
	Short-term schedule risk (higher score = lower risk)	2	5	10	5	10	5	10	5	10
Operations				19		18		19		19
	Amenable to internal operations	1	7	7	6	6	7	7	6	6
	Amenable to external operations	1	7	7	6	6	6	6	7	7
	Amenable to opportunistic sampling	1	5	5	6	6	6	6	6	6
Ownership				28		24		25		20
	Suitability for academic ownership	1	7	7	5	5	6	6	4	4
	Suitability for federal ownership	1	8	8	8	8	7	7	9	9
	Suitability for state/local ownership	1	7	7	7	7	6	6	3	3
	Suitability for private-party ownership	1	6	6	4	4	6	6	4	4
		Sub-total		287		324		303		290
		Grand Total		469		494		459		466

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Table 12. First iteration Trade Study for Basin-wide design area.

			Fixed Platforms		Field Campaigns		Mobile Platforms		Remote Sensing	
Criteria	Sub-criteria	Criteria Ranking (0-6)	Raw Score (0-10)	Weighted Score	Raw Score (0-10)	Weighted Score	Raw Score (0-10)	Weighted Score	Raw Score (0-10)	Weighted Score
Platform intrinsic criteria										
Functional Requirements				14		10		12		9
	Does not need further analyses / post-processing	1	8	8	7	7	8	8	3	3
	Supports year round sampling	1	6	6	3	3	4	4	6	6
Operational Requirements				22		19		23		20
	Ease of deployment	1	7	7	4	4	6	6	7	7
	Flexibility	1	5	5	7	7	7	7	3	3
	Scalability	2	5	10	4	8	5	10	5	10
Technical risk (higher scores=lower risk)				90		89		83		97
	Reliability	3	7	21	7	21	7	21	7	21
	Maintainability	1	7	7	8	8	7	7	9	9
	Availability	1	8	8	6	6	6	6	9	9
	System Safety	1	8	8	9	9	7	7	10	10
	Quality (QA/QC)	3	8	24	9	27	7	21	7	21
	Human Factors	1	8	8	5	5	6	6	8	8
	Environmental Impact (high score => low impact)	1	7	7	6	6	8	8	10	10
	Hazardous Materials (high score => low use of haz. materials)	1	7	7	7	7	7	7	9	9
System maturity				24		30		18		15
	System maturity	3	8	24	10	30	6	18	5	15
Support				33		30		28		28
	Developmental support	1	7	7	8	8	5	5	5	5
	Logistics support	1	6	6	5	5	5	5	8	8
	Engineering support	1	6	6	6	6	5	5	6	6
	Testing support	1	6	6	7	7	6	6	5	5
	Ease of data integration	1	8	8	4	4	7	7	4	4
		Sub-total		183		178		164		169
Management issue dependent criteria										
Functional requirements				63		45		51		54
	Ability to measure relevant parameters	5	7	35	5	25	7	35	6	30
	Ability to provide appropriate sensor placement	4	7	28	5	20	4	16	6	24
Performance Requirements				50		51		63		84
	Provides adequate spatial coverage	3	3	15	5	25	7	35	10	50
	Provides adequate spatial resolution	3	4	8	7	14	8	16	8	16
	Provides adequate temporal resolution (sampling frequency)	3	9	27	4	12	4	12	6	18
Programmatic Requirements				18		14		16		20
	Ability to address other user needs (IOOS, GLRI, etc.)	2	9	18	7	14	8	16	10	20
Cost (higher scores = lower cost)				56		24		40		80
	Development cost (higher score = lower cost)	3	7	21	3	9	5	15	10	30
	Lifecycle cost (higher score = lower cost)	5	7	35	3	15	5	25	10	50
Financial opportunity				31		35		28		35
	Amenable to steady funding (federal, state etc.)	2	8	24	9	27	7	21	9	27
	Amenable to opportunistic funding	2	7	7	8	8	7	7	8	8
Schedule risk (higher scores=lower risk)				26		27		24		28
	Long-term schedule risk (higher score = lower risk)	1	7	7	8	8	6	6	8	8
	Medium-term schedule risk (higher score = lower risk)	1	7	7	7	7	6	6	8	8
	Short-term schedule risk (higher score = lower risk)	2	6	12	6	12	6	12	6	12
Operations				22		21		22		22
	Amenable to internal operations	1	8	8	7	7	8	8	7	7
	Amenable to external operations	1	8	8	7	7	7	7	8	8
	Amenable to opportunistic sampling	1	6	6	7	7	7	7	7	7
Ownership				32		28		29		24
	Suitability for academic ownership	1	8	8	6	6	7	7	5	5
	Suitability for federal ownership	1	9	9	9	9	8	8	10	10
	Suitability for state/local ownership	1	8	8	8	8	7	7	4	4
	Suitability for private-party ownership	1	7	7	5	5	7	7	5	5
		Sub-total		298		245		273		347
		Grand Total		481		423		437		516

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Table 13. Second iteration Trade Study for central basin of Lake Erie end-to-end case study.

			6 buoys; sensors at drinking water intakes		5 buoys, drinking water intakes, semi-monthly field campaigns during summer months		4 buoys, drinking water intakes, semi-monthly AUV deployment during summer months	
Criteria	Sub-criteria	Criteria Ranking (0-6)	Raw Score (0-10)	Weighted Score	Raw Score (0-10)	Weighted Score	Raw Score (0-10)	Weighted Score
Platform intrinsic criteria								
Functional Requirements				12		11		11
	Does not need further analyses / post-processing	1	7	7	6	6	6	6
	Supports year round sampling	1	5	5	5	5	5	5
Operational Requirements				17		17		18
	Ease of deployment	1	7	7	7	7	7	7
	Flexibility	1	5	5	5	5	7	7
	Scalability	1	5	5	5	5	4	4
Technical risk (higher scores=lower risk)				90		91		85
	Reliability	3	7	21	7	21	6	18
	Maintainability	1	7	7	7	7	7	7
	Availability	1	8	8	8	8	8	8
	System Safety	1	8	8	8	8	8	8
	Quality (QA/QC)	3	8	24	9	27	8	24
	Human Factors	1	8	8	7	7	6	6
	Environmental Impact (high score = low impact)	1	7	7	6	6	7	7
	Hazardous Materials (high score = low use of haz. materials)	1	7	7	7	7	7	7
System maturity				24		24		21
	System maturity	3	8	24	8	24	7	21
Support				33		32		32
	Developmental support	1	7	7	7	7	7	7
	Logistics support	1	6	6	6	6	5	5
	Engineering support	1	6	6	6	6	6	6
	Testing support	1	6	6	6	6	7	7
	Ease of data integration	1	8	8	7	7	7	7
		Sub-total		176		175		167
Management issue dependent criteria								
Functional requirements				77		90		85
	Ability to measure relevant parameters	5	9	45	10	50	9	45
	Ability to provide appropriate sensor placement	4	8	32	10	40	10	40
Performance Requirements				75		82		83
	Provides adequate spatial coverage	3	5	15	7	21	7	21
	Provides adequate spatial resolution	3	5	15	7	21	9	27
	Provides adequate temporal resolution (sampling frequency)	5	9	45	8	40	7	35
Programmatic Requirements				70		72		68
	Ability to address design issue (hypoxic intrusion)	6	9	54	9	54	9	54
	Ability to address other user needs (IOOS, GLRI, etc.)	2	8	16	9	18	7	14
Cost (higher scores = lower cost)				56		56		56
	Development cost (higher score = lower cost)	3	7	21	7	21	7	21
	Lifecycle cost (higher score = lower cost)	5	7	35	7	35	7	35
Financial opportunity				34		30		32
	Amenable to steady funding (federal, state etc.)	2	9	18	8	16	9	18
	Amenable to opportunistic funding	2	8	16	7	14	7	14
Schedule risk (higher scores=lower risk)				30		28		28
	Long-term schedule risk (higher score = lower risk)	1	8	8	7	7	7	7
	Medium-term schedule risk (higher score = lower risk)	1	8	8	7	7	7	7
	Short-term schedule risk (higher score = lower risk)	2	7	14	7	14	7	14
Operations				20		18		18
	Amenable to internal operations	1	7	7	7	7	7	7
	Amenable to external operations	1	8	8	7	7	7	7
	Amenable to opportunistic sampling	1	5	5	4	4	4	4
Ownership				31		30		30
	Suitability for academic ownership	1	7	7	7	7	7	7
	Suitability for federal ownership	1	9	9	9	9	9	9
	Suitability for state/local ownership	1	7	7	7	7	7	7
	Suitability for private-party ownership	1	8	8	7	7	7	7
		Sub Total		393		406		400
		Grand Total		569		581		567

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Table 14. Second iteration Trade Study for Lake Michigan End-to-End Case Study.

			Fixed Platforms		Field Campaigns		Mobile Platforms	
Criteria	Sub-criteria	Criteria Ranking (0-6)	Raw Score (0-10)	Weighted Score	Raw Score (0-10)	Weighted Score	Raw Score (0-10)	Weighted Score
Platform intrinsic criteria								
Functional Requirements				10		13		11
	Does not need further analyses / post-processing	1	6	6	7	7	5	5
	Supports year round sampling	1	4	4	6	6	6	6
Operational Requirements				18		17		18
	Ease of deployment	1	7	7	6	6	8	8
	Flexibility	1	6	6	7	7	5	5
	Scalability	1	5	5	4	4	5	5
Technical risk (higher scores=lower risk)				87		85		87
	Reliability	3	7	21	7	21	7	21
	Maintainability	1	7	7	6	6	7	7
	Availability	1	7	7	6	6	7	7
	System Safety	1	7	7	7	7	7	7
	Quality (QA/QC)	3	8	24	8	24	7	21
	Human Factors	1	7	7	7	7	7	7
	Environmental Impact (high score = low impact)	1	7	7	7	7	9	9
	Hazardous Materials (high score = low use of haz. materials)	1	7	7	7	7	8	8
System maturity				24		21		18
	System maturity	3	8	24	7	21	6	18
Support				32		31		29
	Developmental support	1	8	8	7	7	6	6
	Logistics support	1	5	5	5	5	5	5
	Engineering support	1	6	6	5	5	5	5
	Testing support	1	7	7	6	6	6	6
	Ease of data integration	1	6	6	8	8	7	7
		Sub-total		171		167		163
Management issue dependent criteria								
Functional requirements				66		51		56
	Ability to measure relevant parameters	5	9	45	6	30	7	35
	Ability to provide appropriate sensor placement	3	7	21	7	21	7	21
Performance Requirements				75		80		79
	Provides adequate spatial coverage	3	7	21	8	24	7	21
	Provides adequate spatial resolution	5	6	30	7	35	8	40
	Provides adequate temporal resolution (sampling frequency)	3	8	24	7	21	6	18
Programmatic Requirements				60		50		54
	Ability to address design issue (nearshore/offshore gradients)	6	8	48	6	36	7	42
	Ability to address other user needs (IOOS, GLRI, etc.)	2	6	12	7	14	6	12
Cost (higher scores = lower cost)				43		47		48
	Development cost (higher score = lower cost)	3	6	18	4	12	6	18
	Lifecycle cost (higher score = lower cost)	5	5	25	7	35	6	30
Financial opportunity				30		28		26
	Amenable to steady funding (federal, state etc.)	2	8	16	7	14	7	14
	Amenable to opportunistic funding	2	7	14	7	14	6	12
Schedule risk (higher scores=lower risk)				27		26		27
	Long-term schedule risk (higher score = lower risk)	1	8	8	7	7	7	7
	Medium-term schedule risk (higher score = lower risk)	1	7	7	7	7	8	8
	Short-term schedule risk (higher score = lower risk)	2	6	12	6	12	6	12
Operations				22		21		21
	Amenable to internal operations	1	7	7	7	7	7	7
	Amenable to external operations	1	7	7	7	7	7	7
	Amenable to opportunistic sampling	1	8	8	7	7	7	7
Ownership				25		28		26
	Suitability for academic ownership	1	6	6	7	7	7	7
	Suitability for federal ownership	1	7	7	7	7	7	7
	Suitability for state/local ownership?	1	6	6	7	7	6	6
	Suitability for private-party ownership	1	6	6	7	7	6	6
				348		331		337
		Grand Total		519		498		500