

Design of an Agricultural Runoff Monitoring & Incentive System for Maryland

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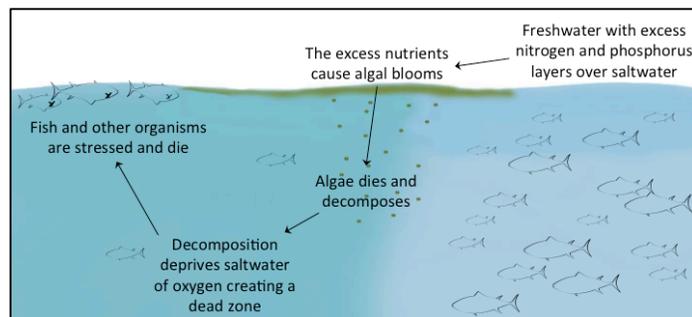
Abstract: The Chesapeake Bay is currently polluted with excess nitrogen and phosphorus coming from agricultural runoff. To reduce agricultural runoff, systems must be introduced to monitor nutrient levels on farmland and incentivize farmers to adopt best management practices. This project uses the Upper Chesapeake Bay in Maryland as a case study. Results indicate that unmanned aerial vehicles (UAVs) with a multispectral imagery subsystem would offer the greatest balance of cost and utility for monitoring farmland. However, because legalizing commercial-use of UAVs is currently in process with the Federal Aviation Administration (FAA), it is recommended that a manned aircraft with a multispectral imagery subsystem be used to test a proof of concept with a category-based incentive system framework. If this proof of concept succeeds and UAVs are legalized for commercial-use, move to a UAV platform for sustained monitoring operations.

Keywords: Agricultural Runoff, Monitoring System, Spectral Imaging, Incentives

1. Introduction

Water pollution comes in multiple forms, including an imbalance of nutrients accumulating in the waters. While these nutrients, such as nitrogen and phosphorus, are essential to a balanced aquatic ecosystem, too much of the nutrients can lead to dead zones. Dead zones are uninhabitable for living organisms and kill off much of the life in the water, affecting the aquatic ecosystem, deterring recreational use, and hurting small businesses that rely on the waters.

Figure 1. Excess Nutrients and Dead Zones (“Harmful Algal Blooms,” n.d.)

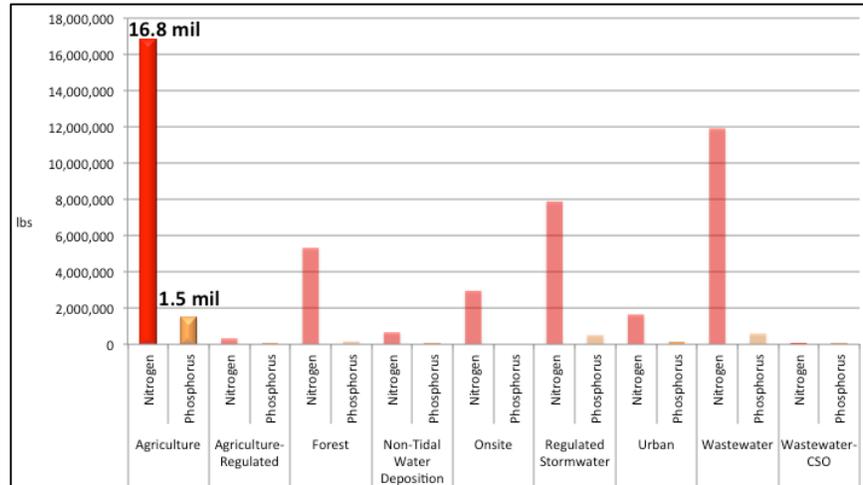


2. Context

The EPA classifies water pollution sources as point and nonpoint sources. Point sources are static and clearly identifiable. Nonpoint sources are dynamic and spread over a wide area from uncontrolled sources. Agricultural runoff is an example of nonpoint source pollution. As farmers fertilize their crops and their animals defecate, nitrogen and phosphorus is left in the ground. When there is rainfall or snowmelt, the water runs across the ground and carries these nutrients into nearby bodies of water. Research has shown that much of the excess nutrients entering the Chesapeake Bay are from agricultural runoff. Over-fertilized crops, pesticides, livestock manure, and other farm operations greatly contribute to agricultural runoff,

which is 41% greater in nitrogen contribution and 152% greater in phosphorus contribution than the second greatest contributor, wastewater runoff. (“What is Nonpoint Source Pollution,” n.d.)

Figure 2. ChesapeakeStat data in 2013 for Maryland



3. Stakeholder Analysis

The primary stakeholders identified for this case study include the West/Rhode Riverkeeper, the Maryland farmers, and the EPA. The West/Rhode Riverkeeper strives to protect rivers and streams in the West and Rhode River watershed from pollution through community relations, monitoring for compliance with environmental laws, promoting restoration, and advocating better environmental policies (“West Rhode Riverkeeper,” n.d.). The Maryland farmers impact the issue of water pollution by the excess nutrients they generate during farm operations. Farmers are the primary actors involved in agricultural runoff. The EPA pursues and promotes environmental protection by encouraging “national efforts to reduce environmental risk”, establishing environmental policies, funding environmental agencies and organizations, and ensuring that “laws protecting human health and the environment are enforced fairly and efficiently” (“Our Mission and What We Do,” n.d.).

4. Problem & Need

The EPA’s Clean Water Act currently addresses pollution issues for point source pollution such as from pipes, channels, and concentrated animal feeding operations. However, addressing nonpoint source pollution such as agricultural runoff is still an open issue.

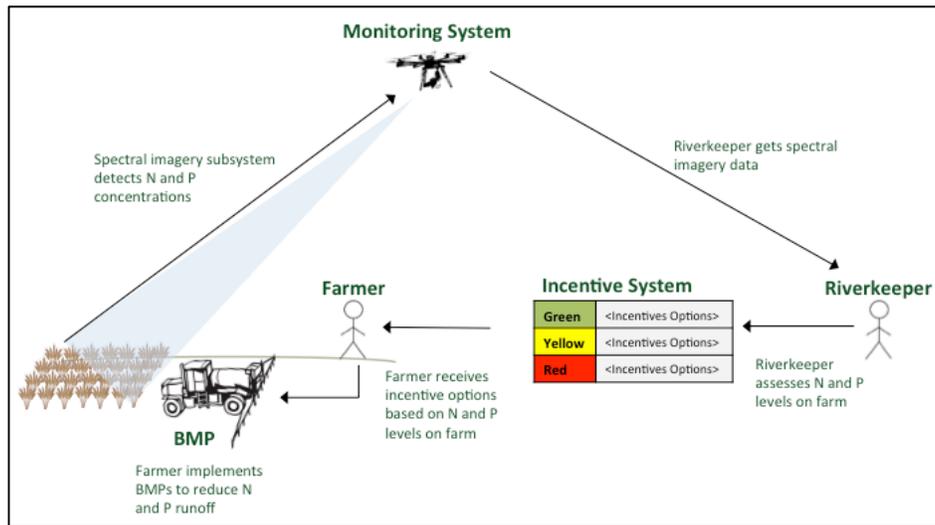
In order to reduce excess nutrients from entering the Chesapeake Bay watershed, systems must be introduced to remotely, and non-intrusively monitor progress on farms. An incentive system must also be introduced to encourage farmers to adopt Best Management Practices (BMPs) for reducing excess nutrients in agricultural runoff.

5. Concept of Operations (CONOP)

5.1 Requirements

- R.1 The monitoring system shall detect nitrogen and phosphorus levels.
- R.2 The monitoring system shall be nonintrusive to farmers.
- R.3 The monitoring system shall be remote.
- R.4 The incentive system shall positively encourage farmers to introduce Best Management Practices (BMPs).

Figure 3. CONOP



6. Monitoring System Alternatives

A technique that can be used to detect nitrogen and phosphorus levels is spectral imagery. As objects on the ground absorb sunlight, they give off reflectance. This reflectance can be captured with a camera and graphed based on its intensity versus wavelength. Depending on the wavelengths at which the light peaks, this can be correlated to a specific element’s spectral signature, which is unique for all elements. Multispectral and hyperspectral imagery subsystems are the primary types used today. The main difference between the two types of spectral imagery subsystems is the bandwidth of the signatures it can capture and the number of bands. Hyperspectral imagery subsystems offer narrower bandwidths and greater number of spectral bands, however, they also come at a significantly higher cost (\$35,000 for hyperspectral versus \$4,000 - \$6,000 for multispectral) (“AisaEAGLE Hyperspectral System,” n.d.) (“ADC,” 2011).

In order to monitor sections of land with spectral imagery, a spectral imagery subsystem must be mounted on a vehicle platform. Four high-level types of vehicle platforms have been identified for this analysis: ground, unmanned aerial vehicles (UAVs), manned aerial vehicles, and satellites. UAVs are further broken down into rotorcraft and fixed-wing types due to their differing average velocities. For analysis purposes, manned aerial vehicles are evaluated at distances of 500 ft above ground level (AGL) and 3,000 ft AGL based minimum height requirements mandated by the Federal Aviation Administration (FAA) and maximum height requirements based on the limitations of the less robust multispectral imagery subsystem (“FAA Code of Federal Regulations,” 2015) (“ADC,” 2011).

7. Incentive Alternatives

The proposed incentive system is based on three levels of classification of farms – green, yellow, and red. These level classifications will be based on a normalized difference vegetation index (NDVI), which determines the density of healthy vegetation by calculating the ratio between near infrared (NIR) and visible light (VIS) wavelengths reflecting off the Earth. An NDVI of 1 indicates healthy vegetation whereas 0 indicates no vegetation. NDVI is calculated by (“Measuring Vegetation (NDVI & EVI),” n.d.),

$$NDVI = \frac{NIR - VIS}{NIR + VIS} \quad (1)$$

Farms will be classified into green, yellow, or red categories based on the following NDVI ranges:

Table 1. Incentive Categories and Associate NDVIs

Green	0.8 – 1.0
Yellow	0.4 – 0.7
Red	0.0 – 0.3

The proposed monitoring system will periodically track nitrogen and phosphorus concentrations on farms in order to identify which level a farm falls under. Depending on which level a farm is classified as, the farmer will be offered incentive options based on that level. The specific incentive options incorporated into each level will be determined following weight elicitation from the West/Rhode Riverkeeper in regards to the following options:

1. A nitrogen and phosphorus report informing farmers of the nitrogen and phosphorus concentration on their farm.
2. A TMDL Goal Membership Card, which would get farmers discount with local area businesses.
3. An awareness report of current federal and state programs that farmers can take advantage of.
4. A legislation change for Farmer’s Insurance to extend coverage to BMP implementation, mitigating risks for farmers introducing new BMPs on their farm.
5. A legislation change for a technology assistance program that would aid farmers who may not be able to afford BMP systems.

8. Method of Analysis

A stochastic simulation was developed for purposes of comparing the accuracy of multispectral and hyperspectral imagery subsystems. The input parameters for the spectral imagery subsystem are the spectral range and spectral resolution. Based on typical element concentrations found in plant growth, a distribution of chemical elements and concentrations in parts per million (ppm) is used as a constant, which the imagery subsystems “detect” in the simulation. Error is incorporated by using a normal distribution with 95% confidence with the tails being determined based on the percent error input into the simulation model. The mean of these distributions is the actual relative intensity at a given wavelength. The purpose of this simulation is to compare the error rates of multispectral and hyperspectral imagery subsystems used in this analysis and determine whether a multispectral system would be sufficient for the purposes of tracking nutrient levels on farmland.

Analysis of the monitoring systems was based on the cost versus performance of the vehicle platforms and accuracy comparison of multispectral and hyperspectral imagery subsystems. Based on studies conducted by the Lincoln Laboratory at the Massachusetts Institute of Technology (MIT), area coverage rate (ACR) can be calculated based on the proportionality given ground sample distance (GSD), signal-to-noise ratio (SNR) squared, and number of spectral bands (K) (Shaw & Burke, 2003). Other equation parameters include height about ground (h_g), focal length (c_k), aperture size (d), and velocity (v). Combining the equations for ACR, GSD, and SNR^2 give (4).

$$ACR \propto \frac{GSD^4}{SNR^2 \times K^4} \quad (2)$$

$$GSD = (pixel\ size) \times \frac{h_g}{c_k} \quad (3)$$

$$SNR^2 = \frac{d^2 \times GSD^3}{v \times K} \quad (4)$$

$$ACR \propto \left(\frac{pixel\ size}{d^2 \times K^3 \times c_k} \right) (h_g \times v) \quad (5)$$

By making the assumption that all vehicle platforms housed the same spectral imagery subsystem for purposes of comparison, a unitless coefficient was derived to represent the imagery subsystem parameters. According to the manufacturer for the fixed-wing UAV used in this analysis, their UAV has an area-coverage of 250 acres for a 40-minute runtime (“Aero-M,” n.d.). This was converted into units of km^2/min and substituted into (5) along with the minimum velocity and height above ground, which will be evaluated at 400 ft. above ground level based on current FAA regulations for hobby UAVs (“FAA Code of Federal Regulations,” 2015). The resulting equation for ACR is

$$ACR \propto 10.8089 (h_g \times v) \quad (6)$$

9. Results

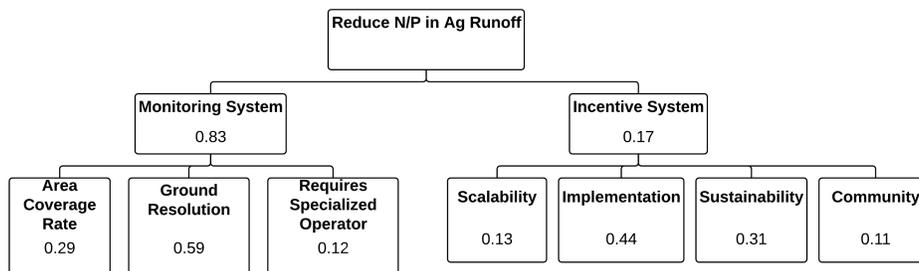
The spectral imagery simulation was run for 100,000 iterations at 1.0%, 3.0%, 6.0%, and 9.0% device error rates for the multispectral and hyperspectral imagery subsystem. The determined concentration for nitrogen and phosphorus were compared to the actual concentration in the simulation to calculate the detection error for nitrogen and phosphorus amongst the noise of other elements. An average was taken for the mean detection error for nitrogen and phosphorus and plotted against the device error in order to compare the error trends for multispectral and hyperspectral imagery subsystems.

The percent difference between detection errors for the multispectral and hyperspectral subsystems ranged from 0.3% at 1.0% device error to 2.4% at 9.0% device error. Device error can vary slightly for a multispectral imagery subsystem depending on the environment the system is used in, however, the manufacturer has noted that this device error can generally be expected to be within 2%. When the simulation was run at 3.0% device error, the percent difference between multispectral and hyperspectral was 0.9%

Multispectral system costs range from \$3,000 to \$6,000 whereas hyperspectral systems cost \$29,000 and up. With the minimal difference in detection error between multispectral and hyperspectral systems, a multispectral system would be adequate for purposes of monitoring nutrient levels on farmland (“ADC,” 2011) (“Pika II,” n.d.).

Weights were elicited from the West/Rhode Riverkeeper for this case study. The weights were based on ACR, ACR per dollar, and ground resolution for the monitoring systems. For the incentive system, the weights were based on implementation, sustainability, scalability, and the sense of community associated with each incentive alternative.

Figure 4. Value Hierarchy with Weights



Based on the weights elicited by the Riverkeeper, the rankings for the monitoring system alternatives were ranked and subsequently graphed in a cost-utility analysis. The incentive system alternatives scored based on normalized t-scores.

Figure 5. Cost-Utility Analysis of Monitoring Alternatives

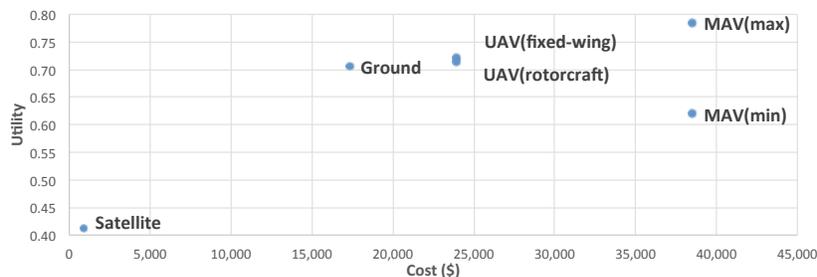


Table 2. Incentive Alternative Scores

Incentive Alternatives	Scalability	Implementation	Sustainability	Community	Total Weighted Scored
	0.0221	0.0748	0.0527	0.0187	
N & P Report	1.50	1.72	1.37	3.14	0.29
TMDL Goal Membership Card	2.75	0.74	3.09	2.75	0.33
Awareness Report	0.25	2.95	0.34	1.18	0.27
Farmer’s Insurance Legislative Change	2.25	1.97	2.06	0.78	0.32
Assistance Program Legislative Change	2.25	1.97	2.06	0.78	0.32

9. Recommendation & Conclusion

While the ground monitoring system shows high utility for lower cost, this system fails the requirement for the monitoring system to be non-intrusive. While both rotorcraft and fixed-wing UAVs have the best balance of cost and utility, commercial use of UAVs are currently illegal as of March 2015. The FAA published a Notice of Proposed Rule-Making (NPRM) in February of 2015 to officially move toward legalizing commercial of UAVs in the United States. This NPRM proposes an incremental approach to UAV legalization starting with agricultural applications (“Operation and Certification of Small Unmanned Aircraft Systems,” 2015).

Based on utility rankings, the TMDL Membership Goal Card ranked highest with both legislative changes for the Farmer’s Insurance extension and the Assistance Program were tied in second. The nitrogen and phosphorus report ranked third and the awareness report for currently existing federal and state programs beneficial to the farmers ranked last. Based on these rankings, the incentive options were arranged in the following incentive system framework:

Table 3. Incentive System Framework

Category	NDVI	Incentive Options
Green	0.8 – 1.0	TMDL Membership Goal Card
		Farmers Insurance Legislation Change
		Assistance Legislation Change
		Nitrogen & Phosphorous Report
		Awareness Report
Yellow	0.4 – 0.7	Farmers Insurance Legislation Change
		Assistance Legislation Change
		Nitrogen & Phosphorous Report
		Awareness Report
Red	0.0 – 0.3	Farmers Insurance Legislation Change
		Assistance Legislation Change

It is recommended that the West/Rhode Riverkeeper utilize a manned aerial vehicle with a multispectral imagery subsystem in order to test a proof of concept for monitoring farmland in conjunction with the incentive system. If this proof of concept succeeds and a new FAA Regulation (FAR) is devised legalizing commercial-use of UAVs for agricultural applications, move to a UAV platform for sustained operations monitoring farmland.

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