ABSTRACT

BACKGROUND: The National Research Council (NRC) advocates adaptive implementation of Total Maximum Daily Load (TMDL) standards as the approach to making progress toward achieving water quality standards in the face of uncertainty and constant change. In arid/semiarid regions, the potential for extreme spatial and temporal variability in hydrologic conditions during land-based training exercises can directly influence the level of associated environmental impacts from non-point source pollutants such as eroded sediment, petroleum products, and heavy metals. To ensure adaptability in managing training operations while minimizing impacts on watersheds, it is necessary to identify military activities that contribute to non-point source pollution, and strategically locate and schedule training activities. Decision tools and associated data are needed that provide the necessary information to articulate tradeoffs between alternative management actions and resultant impacts and/or benefits to training range or adjacent downstream water bodies.

OBJECTIVE: This research is designed to achieve improved understanding of processes contributing to non-point source pollution from military training activities in arid/semiarid regions and to develop impact assessment and decision tools for improved management. Improved management of training lands will help maintain sustainable training facilities and protect water quality and the natural resource base.

SUMMARY OF TECHNOLOGY: A set of decision tools, process models, and GIS databases will be assembled, linked and integrated as an adaptive management framework to minimize constraints on training exercises while ensuring protection of watersheds and compliance with TMDL targets. The decision tools will assist in optimizing design and implementation of operations, management plans, and policies in the face of uncertainties. They will be supported by state-of-the-art watershed/erosion models and GIS models linked to tailored remotely sensed and conventional databases. Advanced pattern recognition techniques will be used to characterize spatial variability and changes in soil and vegetation. The framework will enable comprehensive trade off analyses of multiple interdependent interests including field training operations, watershed and in-stream impact mitigation and habitat restoration, and upstream watershed practices. The framework will be designed to address local, site specific operations, public works projects, and associated effects as well as cumulative processes and effects over a range of scales. The interface to the framework will be entirely through standard web development languages (e.g. HTTP), thereby, ensuring users only need a web browser and access to the INTERNET (or INTRANET) to perform all operational functions.

The practical utility of the adaptive management framework for managing training operation environmental impacts in arid/semiarid regions will be demonstrated at the Yakima Training Center (YTC) where PNNL has considerable experience, knowledge of hydrologic and biological processes, and extensive data. PNNL will collaborate with Dr. Leonard Lane (subcontractor), former Research Leader and Senior Hydrologist at the Agricultural Research Service. Dr. Lane was the lead scientist for development of the Hillslope Erosion Model proposed for use in this project. Dr. Lane has also published and conducted research in the development and use of integrated information systems for rangeland management. Our combined effort will focus on development, demonstration, and delivery of an integrated adaptive framework for effective management of military operations in arid/semiarid regions. Stakeholder/user input will be obtained at each step in the Project and will be especially critical in the technology transfer activities at the YTC.

TRANSITION PLAN: The adaptive framework to be developed under this project will be demonstrated/transferred and made fully operational for use at the YTC on YTC computer systems. YTC staff will be fully instructed in the use of the framework. Materials produced for this technology transfer process will be designed to facilitate broad transfer to other military facilitates as well.

TECHNICAL

SERDP RELEVANCE

This project is designed to deliver several products supporting the objectives of CPSON-03-02 as well as to support implementation of ecosystem management at the Yakima Training Center (YTC) and military training facilities with similar operations and environmental issues. The project will develop, demonstrate, and deploy a comprehensive information and analytic infrastructure and adaptive implementation framework for more effective, streamlined, and integrated operational and environmental planning and decision making at military bases in arid and semiarid regions. This work supports the long-term research goal of CPSON-03-02: "to enhance the science and engineering related to the sustainability of military training and testing ranges".

The proposed research will provide 1) improved understanding of processes contributing to non-point source pollution from military training activities in arid/semiarid regions, and 2) development of impact assessment and decision tools for improved management and sustainability of training exercises. This will be accomplished through an integrated set of decision tools, process models, and GIS databases assembled as an adaptive management framework to minimize constraints on training exercises while ensuring protection of watersheds and compliance with TMDL targets. The practical utility of the adaptive management framework for managing training operation environmental impacts in arid/semiarid regions will be demonstrated at the YTC.

Military training activities that are non-point sources of pollution will be identified using advanced pattern recognition techniques being developed at PNNL. This technique uses sequences of remotely sensed images to detect change at the pixel level, such as a loss of vegetation, and isolate probable conditions (training activities or range fire) contributing to the change. This is done by utilizing ancillary information that may be directly linked to the change (e.g., vehicle location data) or may be tangentially related (proximity to recent range fire). This method is applicable to large areas for rapidly identifying military activities that are potential non-point sources of pollutants. PNNL's extensive image database for the YTC (beginning in 1987) will allow the impacts and recovery from training activities to be tracked in space and time.

The quantity and quality of non-point source runoff from impacted areas will be estimated using current YTC monitoring activities combined with state-of-science distributed hydrologic process and overland erosion and sediment transport modeling. Measurements of erosion and deposition rates collected in twelve sedimentation ponds will be used with stream discharge and suspended sediment concentrations to calibrate and test the hydrologic and sediment transport models. These models will then be used to estimate short and long-term runoff and sediment loading to stream channels (including those supporting endangered and threatened fisheries) where measurements are not available. These models will also be used within the adaptive management framework to estimate impacts from alternative land use/training activities.

State-of-knowledge of the development of Total Maximum Daily Loads (TMDLs) will be advanced through an adaptive combination (framework) of data collection, GIS technologies, and distributed modeling. Advanced distributed model and data management techniques will be used by the adaptive management framework to ensure effective and streamlined data/model integration. This provides the ability to rapidly and continuously improve the calibration of process models with recently obtained data, a key feature when models are used in near real-time forecasting to evaluate alternative management activities. Advanced optimization methods will be used by the adaptive management framework to clearly articulate multiple objective tradeoffs between alternative operational practices and environmental policies. The adaptive management framework will allow managers to optimize training schedules (significantly reducing delays and costs) and locations, thus maximizing land available for training, while minimizing impacts to the watershed and receiving water bodies. The framework will also help ensure

that appropriate erosion and sediment control technologies are deployed at appropriate times and locations to achieve maximum benefits.

TECHNICAL OBJECTIVE

Two principal **objectives** of the proposed project are focused on achieving improved understanding of processes contributing to non-point source pollution from military training activities in arid/semi-arid regions and developing and demonstrating in-stream impact assessment and decision tools for improved management.

1. The **first objective** is to develop an integrated set of decision tools, process models, and GIS databases. These tools and data will be assembled as an adaptive management framework for management of field training activities in arid and semi-arid regions to minimize constraints on scheduling and implementing training exercises while ensuring protection of watersheds and receiving water bodies and compliance with TMDL targets.

2. The **second objective** is to demonstrate the practical utility of the adaptive management framework for managing training operation environmental impacts in arid and semiarid regions. The adaptive implementation framework will be demonstrated at the Yakima Training Center (YTC) where PNNL (located within approximately 40 miles) has considerable experience, knowledge of hydrologic and biological processes, and extensive data.

The purpose of the adaptive management framework is to provide **decision tools** that will assist in optimizing design and implementation of operations, management plans and policies in the face of uncertainties. The decision tools will be supported by state-of-the-art watershed/erosion models and GIS models linked to tailored remotely sensed and conventional databases. The framework will provide the basis for comprehensive trade off analyses of multiple interdependent interests including field training operations, watershed and in-stream impact mitigation and habitat restoration, and upstream watershed practices. The framework will be designed to address local, site specific operations and associated effects as well as cumulative processes and effects over a range of scales (e.g., subwatershed, watershed, basin, etc.)

TECHNICAL APPROACH

The overall approach to this project is to: develop, assemble, link and integrate the tool set for the adaptive management framework; demonstrate its use and value; and operationalize the framework for general application in arid and semiarid regions. The site-specific demonstration will focus on management of training operations and ways to minimize impacts to training areas and downstream receiving waters at the Yakima Training Center in southeastern Washington.

This project will employ several highly advanced technologies:

- Advanced distributed model and data management techniques to ensure effective and streamlined data/model integration.
- Advanced optimization methods to clearly articulate multiple objective tradeoffs between alternative operational practices and environmental policies.
- Advanced remote sensing and GIS methods to characterize spatial variability in soil, vegetation, and antecedent soil conditions.
- Advanced pattern recognition techniques to detect change and isolate conditions contributing to potential sensitivity.
- State-of-science distributed hydrologic process and overland erosion and sediment transport modeling.
- Data mining and linking technology to perform the system integration.

Development, demonstration and deployment of the adaptive framework will be accomplished in five tasks as follows: 1) Project Management; 2) Adaptive Management Framework Development; 3) Remote Sensing and GIS Technologies; 4) Hydrologic and Erosion Modeling; and 5) Integration, Demonstration, Technology Transfer, and Final Report.

In order to fully maximize the time and budget for this project, our approach includes full utilization of the extensive existing remote sensing databases and GIS for the YTC, much of which was developed by PNNL and is already resident on PNNL systems. Our team includes the principal authors for both the hydrologic and hillslope erosion models to be use by this project, Dr. Mark Wigmosta (DHSVM) and Dr. Leonard Lane (HEM), respectively, and we plan to leverage ongoing PNNL research related to "smart" change detection and development of integrated information systems to support natural resource management.

Background

One of the stated objectives of CPSON-03-02 is to deliver data and technologies that advance the state-of-knowledge and the ability to model the contributions of DoD non-point source to total maximum daily loads (TMDLs). The objective of the Total Maximum Daily Load (TMDL) program is attainment of ambient water quality standards through the control of both point and non-point source pollution. It is noted by the National Research Council (2001) that related to the paucity of data available in most locations to comply with program requirements, scientific uncertainty is a reality that must considered directly in the process. One of the recommendations of the National Research Council (NRC) is that to enable the TMDL program to proceed in the face of inevitable data and information limitations, TMDL plans should employ an adaptive implementation approach whereby, as plans are implemented, they are periodically reviewed to determine if they are meeting intended objectives. If not, they should then be revised based on scientific data and information.

Adaptive implementation, as described by the NRC (2001), is the process of "…taking actions of limited scope commensurate with available data and information to continuously improve our understanding of a problem and its solutions, while at the same time making progress toward attaining a water quality standard." The notion of adaptive implementation is founded on the concepts of adaptive management which is defined by Walters and Holling (1990) as a systematic and rigorous, scientifically defensible program of learning from the outcomes of management actions, accommodating change, and improving management. While generally advocated, adaptive management has proven difficult to implement in part due to the lack of readily available, widely implemented tools for resolving critical natural resource management issues (scientific methods for analyzing, understanding, and managing problems within complex and anthropogenically altered environmental systems). The NRC (1999) discusses the need to provide resource managers the means to apply such tools (e.g., simulation models) more routinely. Such systems have been developed for a variety applications [e.g., pest management (Berry et al., 1991); simulation model parameterization (Ritchie, 1989); and natural resource planning (Schmoldt and Rauscher, 1996)] and Thom (2000) describes a conceptual approach for adaptive management of ecosystem restoration projects. However, there remains the need for system tools to "operationalize" the adaptive management process for comprehensive ecosystem management.

The Yakima Training Center (YTC), located in the arid, high desert region of southeastern Washington, contains a number of tributaries that flow into 303d listed streams, including the Yakima River. Elevated water temperatures and increased sediment loads have contributed to a significant loss of usable habitat for Endangered Species Act (ESA)-listed species in large portions of these receiving streams. Estimation of current mobile sediment quantities and sources is a major concern for the YTC, and a high priority concern for DoD lands. Most erosion (and transport) occurs in the YTC during extreme events of short duration, often associated with rapid rain-induced snowmelt. Erosion potential can be further enhanced following natural or man-induced range fires. It is infeasible to make management decisions based

entirely on empirical data, given the infrequent nature of these events and the need to consider alternative land management scenarios.

As noted by the YTC (2002), the intent of ecosystem management on military lands is to attain "sound and informed environmental protection and natural resource management while permitting planned development and sound military operations." At the YTC, as outlined in their Cultural and Natural Resource Management Plan (CNRMP), an adaptive management approach has been adopted. Watershed assessments are being conducted to comprehensively characterize the human, aquatic, riparian and terrestrial features condition, processes and interactions on a watershed basis. This information can ultimately aid in the identification and implementation of the most advantageous management actions and land use decisions (e.g., timing and location of training operations, road construction or closure, ecosystem restoration, etc.). A similar approach is being implemented at the Ft. Carson Military Reservation (FCMR). As described by Lane et al. (1999), at the FCMR a system is being developed that integrates data, knowledge and process simulation to assess soil/site stability. The ultimate goal of the system is to provide the FCMR a tool to conduct rangeland health assessments to support rangeland management on training lands.

For ecosystem management at the YTC, an adaptive combination of data collection and distributed modeling is required to properly manage military operations to minimize environmental impacts. Such a framework will allow managers to optimize training schedules and locations, thus maximizing land available for training, while minimizing impacts to the watershed and receiving water bodies. The framework will also help ensure that appropriate erosion and sediment control technologies are deployed at appropriate times and locations to achieve maximum benefits.

Methods

This project is designed to deliver several products supporting the objectives of CPSON-03-02 as well as directly support implementation of ecosystem management at the YTC and military training facilities with similar operations and environmental issues. The project will develop, demonstrate, and deploy a comprehensive information and analytic infrastructure (or framework) and adaptive implementation methodology for more effective, streamlined, and integrated operational and environmental planning and decision making at military bases in arid and semi-arid regions. This framework will provide the ability to defensibly, consistently and rapidly evaluate alternative operational practices and environmental policies (e.g., TMDLs). The framework will integrate data, models, and decision tools in order to advance the effectiveness of training range operational decision-making.

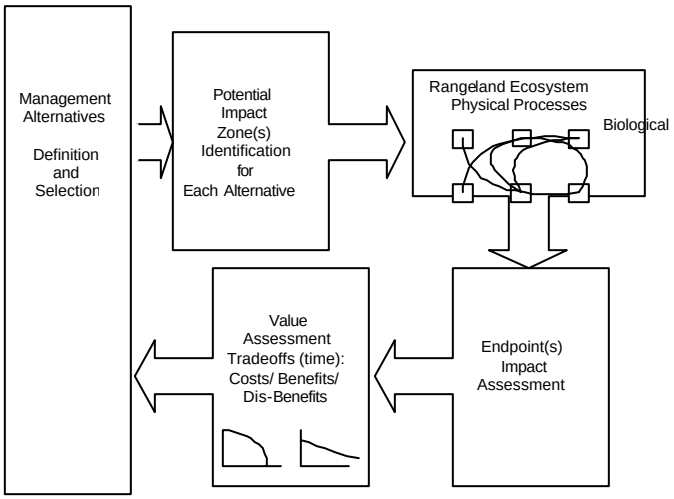
Task 1. Project Management

The management of this project will be under the direction of Dr. Mark Wigmosta. He will be responsible for ensuring each task in completed on schedule and within budget, as well as technology transfer and final reporting. Key components of this research will be coordination and interaction with the full research team, including the PNNL team, Dr. Leonard Lane (subcontractor), and the Public Works staff at the YTC.

Task 2. Adaptive Management Framework

Adaptive Management Process

The general process for adaptive implementation of ecosystem management including measures to achieve TMDLs at rangeland-based military training facilities is shown in the figure below. Key steps in the development of the adaptive management framework are assembly of the data and process modeling components as discussed below in Tasks 3 and 4. The iterative process begins with the definition and selection of a subset of management (e.g., operation or restoration) alternatives. Guided by initial screening of alternative management actions and preliminary assessments of how they might affect



rangeland conditions, relevant existing and new rangeland characterization data are compiled, collected and analyzed. Data analysis and characterization are conducted in the context of the hillslope hydrology and erosion models which, based on physical and biological processes, established the linkage between training operations, restoration or other management measures and relevant endpoint impacts including soil surfaces, vegetation, receiving streams, etc. These results provide the basis for analyzing the tradeoffs in impacts, costs and other considerations of concern. An elaboration on each step in the process follows:

Step 1 - Management Alternatives Definition and Selection: Overall resource management goals at YTC, FCMR, and similar military installations are to achieve conservation goals while minimizing potential adverse impacts to habitat or military training. In pursuing this balance, a diverse range of activities and their interactions and inter dependencies must be considered. The primary activities (military training, public works actions, and natural resource management) are briefly described below.

Military Training: In simplified term, the principal military training management actions at YTC (2002) consists of:

- Rotation of training area use across the twenty-six developed areas.
- Scheduling of training activities (e.g., individual and crew gunnery, small arms, engineer and communication, collective maneuvers, etc.).
- Use of terrain for movement and concealment.

Decisions regarding these actions must consider historical use, current military requirements, evolving missions, deployment costs (e.g., costs/mile of transport to training sites), and environmental practices and policies. For example, the YTC is divided into five Land Use zones:

- Land Bank where resource protection and restoration are priorities.
- Conservation where most forms of training are permitted but are highly controlled.
- General Use where all forms of training are permitted with the condition that surface water quality, soil stability, and long-term habitat resources are maintained.
- High Use where heavy use and high impacts are accommodated while reclamation and/or remediation actions are used to protect soil and water resources.
- Impact Areas which are off –limits due to unexploded ordnance.

In addition to use policies, other factors effect the evaluation of military training alternatives such as recent or forecast weather events, range fire or other conditions that exacerbate the potential for short- or long-term environmental disturbance.

Public Works: Other land use and management actions that must be considered in conjunction with military actions are road construction and closure, recreation, cultural resource management, and fire management.

Natural Resource Best Management Practices (BMPs): Site-specific experience and expertise have been developed to maintain natural and cultural resources. The YTC has an established array of BMPs to limit erosion and other impacts that have specific attributes including costs, schedule requirements, impact on land availability, etc. Examples include:

- Pre-planning with Using Units to balance meeting mission requirements with minimizing disturbance.
- Revegetation subsequent to military operation impacts.
- Upgrade heavily used roads to control erosion.
- Road maintenance following large maneuvers.
- Rotate training areas to allow recovery of vegetation and soils.
- Limit maneuvers in areas where soils are saturated.
- Continue monitoring and evaluation processes to support ongoing adaptive management.

Step 2 – Potential Impact Area Identification: For each candidate management alternative, the GIS, remote sensing and other data to be developed in Task 3 will provide the means to identify areas that may be affected by proposed management actions. As necessary site maps can be generated as well as inventories of resources, current hydrologic condition, use history, etc.

Step 3 - Rangeland Ecosystem Processes: This step involves analysis of potential impacts of proposed management actions to soil conditions, vegetation, and other factors that can be reflected in the process model parameterization. Details of this step are discussed in Task 4.

Step 4 - Endpoint Impact Assessments: The results of the rangeland ecosystem process modeling provide the measure of impacts to the designated areas, including erosion, sedimentation, and sediment loading to receiving streams for each of the management alternatives analyzed.

Step 5 - Value Assessment: In this step, for each of the alternatives being considered (i.e., military training strategies, public works actions, resource management actions), endpoint impacts and all other evaluation criteria are evaluated within a comprehensive trade-off analysis. Results can be generated as graphical two-dimensional tradeoff curves (e.g., cost vs. eroded area for all alternatives) for the complete set of criteria or as summary matrices.

Step 6 – Definition and Selection: Completing an iteration of the process, the current analysis can be deemed complete if results are satisfactory, or previous alternatives can be adjusted, new alternatives can be defined, and the process repeated.

Adaptive Management System

The adaptive management framework is realized through a metadata database (MDDB) and suite of software programs designed to interact specifically with the MDDB. The database and programs are transportable and can be applied using any standard commercial database system. PNNL will work closely with the YTC staff to ensure that the database will leverage off their existing computational infrastructure and not represent a new software mortgage. The software will be implemented in C/C++ or Java using standard language features to ensure the software elements are fully portable. The interface to the framework will be entirely through standard web development languages (e.g. HTTP), thereby, ensuring users only need a web browser and access to the INTERNET (or INTRANET) to perform all operational functions.

The framework is designed to provide the essential requirements of accountability, accessibility, and adaptability:

Accountability

- Clearly articulate the tradeoffs between multiple objectives alternative management and operations scenarios.
- Communicate the likelihood of making decision errors that result from model and data uncertainty.
- Create a bias towards robust alternatives.
- Facilitate the sharing of process knowledge across bases having similar conditions and/or environmental management challenges.
- Show the models, data, and assumptions used to reach decisions.

Accessibility

- Provide reliable and rapid access to models, data, and the rationale that underpin decisions.
- Provide the ability to "drill-down" through decisions, data, and models.
- Ensure maximum access by being Web-accessible.

Adaptability

- Incorporate a modular modeling design that allows new data and models to be integrated into analyses.
- Support of real-time data assimilation by providing tools to automate the calibration process.
- Provide tools required to directly support adaptive management

These critical framework requirements will be achieved through development of a set of three software toolboxes (decision toolbox, model toolbox, and data toolbox). The decision toolbox clearly articulates the tradeoffs and controls data and model toolboxes. The model toolbox integrates and shares models and process knowledge, and the data toolbox enables web-based data management.

Due to the sequential nature of adaptive management, the framework must efficiently coordinate very large sets of feasible action sequences and their predicted outcomes. Particularly given that for many actions, the impacts may have recovery times of years. If the action sequences are too numerous to feasibly define or manage, the framework can manage patterns of actions. For instance, the number of possible unique action sequences for ten separate actions that can occur in any of ten time periods is 10^{10}. Clearly, even this relatively simple environmental problem would exceed the ability of current (and likely next generation) computers. However, pattern recognition methods can detect common patterns in the optimal next action or identify the need and value to resolve specific conceptual model uncertainties. To provide these pattern recognition functions, the framework contains a variety of intrinsic functions ranging from standard statistical tests to evolutionary computing tools such as artificial neural networks, fuzzy clustering, and genetic algorithms.

The framework will provide users the ability to view tradeoffs between multiple objectives (assessment outcomes) and understand the impact of parameter uncertainty on these objectives. A Java-based multiple objective tradeoff tool will communicate with the MDDB via XML to visually display the tradeoffs. Users interested in understanding the pedigree of the specific outcomes will be able to drilldown from the tradeoff tool and understand the complete history of the assessment. This entire capability will be web-based to ensure transportability and easy access.

The framework approach melds together the perspective of the mechanist and the empiricist. Current process models are not sufficiently reliable to take a purely mechanistic perspective. A purely empirical perspective is unable to extrapolate process knowledge, particularly the impacts of actions outside the limits of past monitored experience. The framework fuses models and observations into an augmented set of realizations. Key to the integration of models with observed data is the ability to rapidly and continuously improve the calibration of process models with recently obtained data. The framework will include a generalized model calibration tool. While this does not eliminate the need for a qualified modeler to interpret model results and select calibration data, it does dramatically increase the effective utilization of the modeler's time. The auto-calibration tool employs the Task Scheduler to manage the repeated running of the process model over a range of calibration parameter values. The tool will employ

a pareto search algorithm to automatically articulate the impact various calibration parameter selections on various calibration objectives. The qualified modeler may select one or more sets of credible calibration parameters, thereby, capturing the parameter uncertainty associated with the specific process models.

The framework's ability to continuously monitor newly arrived data provides an opportunity to detect anomalies. Rapid identification of anomalies between the patterns representing new data with the patterns in the existing baseline, allows the framework to advise users of the occurrence such anomalies. Anomalies may signify a need to modify the conceptual model, recalibrate the models, or reassess the validity of the new data itself. If the anomalies are significant enough, the Event Manager (another framework intrinsic function) sends messages to the appropriate queues or may automatically undertake a specified response (e.g. recalibrate models).

Adaptive management attempts to balance the desire to minimize adverse impacts with the desire to maximize increased process understanding. Since cost is the universal adverse impact, assessing the value of information is a crucial function of any framework that attempts to implement adaptive management. The framework will provide this capability by associated life-cycle costs with various action/monitoring strategies and identifying the likelihood that the specified monitoring would reduce the likelihood of taking the improper action. The framework does not attempt to associate a cost directly with the associated impact but instead communicates the multi-objective tradeoffs with life-cycle cost as one objective and the sequence of actions considered reflects the improved understanding and alternatives afforded by the new information.

Task 3 - Remote Sensing and GIS Technologies:

Training activities that disturb soils can impact the ecosystem through erosion, sediment loading, and temperature alterations to aquatic habitats as well as cause physical destruction of key habitats. Remote imagery can be used to characterize environmental changes across the watershed such as increases in bare soils, changes in vegetative structure, and changes in albedo and temperature patterns. We propose to develop spectral imaging algorithms for use with sequentially collected imagery to assess quantitative and qualitative changes in key landscape characteristics as a result of military training. Landscape characteristics potentially impacted by training that influence watershed processes include relative amounts of upland or riparian vegetative cover and bare soils and the formation of rills, gullies and channels. Image analysis will be used to quantify landscape-level characteristics in several steps: 1) identification and analysis of vegetative and soil indices that best reflect relative quantities of vegetative cover and bare soils, 2) use of these data sets from sequential imagery to detect significant increases or decreases in bare soils as a result of training activities, and 3) application of sophisticated change-detection methods including textural analyses and linear spectral unmixing techniques to optimize the detection and characterization of biotic signatures. Current YTC field sampling will verify the condition and status of vegetation and soil-related habitat characters within and outside areas identified. The image analysis results will then be used in conjunction with topographic data as input data layers for hydrologic modeling to quantify the magnitude and spatial distribution of surface water runoff and sediment loading to streams.

A key component of this research is to define past and current ecological conditions at the YTC and how training exercises have changed conditions through space and time. This research will draw in part on PNNL's extensive database of remotely sensed image data obtained or generated through work at YTC dating back to 1987. Data products include Landsat, SPOT Panchromatic, SPOT Multispectral, and AVIRIS Hyperspectral images; airphotos; land use, fire, vegetation, and soils maps; as well as tracked and wheeled vehicle assessment photos and notes (see Supporting Technical Data, Table 1 for complete details on data format, dates, and resolution). PNNL will process this data along with relevant data from YTC, state, federal, and other sources. Image data, elevation data, soils, vegetation, infrastructure, planning data, engineering data, vehicle location information will be prepared for use. The imagery data

will be orthmetrically corrected and co-registered before multi-temporal analysis is performed. The ground data including notes, photos, and measured values will be placed in a single database to allow immediate access via database management systems including GIS.

PNNL has considerable experience at YTC and other locations tracking vegetation changes over time through a novel stratification and mapping methodology, wherein multispectral signatures are analyzed by existing vegetation polygons. This provides a view of the within-class variability. The signature trajectories can then be tracked over time and combined with a site-specific rule-base to determine most likely vegetation trend. The cover density will be mapped though the use of multi-spectral data analysis and ground data. The ground measurements will be correlated to the observables from the imagery (e.g. soil and vegetation indices) and will be propagated over the entire image space (Cullinan, 2001).

PNNL has a major internal research project for Imagery Science and Technology that is developing a number of advancements in image processing. This proposal will leverage these internal efforts to optimally utilize imagery from different sensors, and to provide improved change detection methods. The internal research has developed novel techniques for using small areas of high spatial resolution imagery to sharpen broad areas of coarse resolution imagery, and for sharpening high spectral resolution imagery with high spatial resolution imagery. The motivation for these approaches to image fusion is to provide methodology that optimizes the use of imagery, saving costs (imagery, processing, storage) to the end user.

Existing change detection methods result in a map that shows only that something is different, not the cause. The new "smart" change detection techniques being developed at PNNL offer improvements over the standard approaches. This new methodology will provide not only pixel level change assessment, but provide confidence metrics about the degree of change at the pixel level. The change detection process then utilizes the pixel level change and confidence values, along with contextual and GIS data, to mimic analyst efforts to create a map of change with probabilities associated. This is done by utilizing ancillary information that may be directly linked to the change (vehicle location data) or may be a tangentially related (proximity to bivouac area). The improvements exploit multi-sensor, multi-scale, and multi-temporal imagery to create an image of change vectors; context-based object sharpening is then applied before exploiting probability data and fed into an automated context-based rule set to explicitly identify features of interest.

For example, if a user has an interest in vegetation loss related to training activities, the model will first detect a negative shift in vegetation signature and then group adjacent changed pixels into objects. The shape, proximity to past training activities or fire, and neighborhood attributes of the objects would be used to prioritize the relevance. Consider a pixel that shows extreme vegetation change located in proximity to a training area, but distant from areas of recent range fire. If this pixel belongs to an object that has a shape consistent with the spatial extent of previous training, the pixel would have a high probability that the detected change is related to training activities and a low probability that it is related to range fire. These improved change detection techniques will provide salient, objective information over large land areas, providing an efficient method to identify activities disturbing natural conditions and are potential non-point sources of pollutants. This method can also be used to track vegetation recovery (positive change).

Remote sensing technologies can rapidly identify areas negatively impacted by military activities and track these changes though time. However, these technologies have limited ability to estimate the magnitude and loading of pollutants or the probable impact of alternative land use. Simulation models are typically required for this type of analysis (Task 4). Remote sensing from space-borne and airborne imaging systems have demonstrated the capability to provide critical characteristics of vegetation and soils at the landscape scales required by watershed models. Important parameters include land cover, plant biomass (LAI, leaf area index), and surface temperature. PNNL has extensive experience in the development of land cover (e.g., vegetation type) based on optimal use of multi-temporal and multi-

sensor imagery with ancillary GIS data sets such as soils maps. For example, by combining important GIS-based data sets and multi-temporal SPOT imagery, a detailed vegetation map can be created, customized, or updated with classes optimized to support the watershed modeling effort. Biomass estimates (LAI) have classically been estimated by regressing vegetation indexes (e.g. normalized difference vegetation index, NDVI) against field measurements (e.g. Link et al.1996). In an analogous manner, recent work by both Department of Defense (e.g., Tweddale et al, 2001) and others (e.g. Cullinan et al., 2001) has demonstrated the utility of interpolating field cover density (or % bare ground) data, over various scales, using remotely sensed images. For estimates of surface temperature, the Landsat Thematic Mapper thermal channel has been used (e.g., Wukelic et al. (1989).

Task 4 - Hydrologic and Erosion Modeling

The YTC has several fish species of interest, including Upper Columbia steelhead and Upper Columbia Spring Chinook that are federally listed as endangered, while Middle Columbia Steelhead are federally listed as threatened (YTC, 2002). YTC streams are designated by the NMFS as critical habitat for these salmonids. The primary water quality concern at YTC is the introduction of fine sediment into streams and discharge to the Yakima and Columbia Rivers. Discharge of fine sediment is most likely following high, short duration overland flow events, typically rain falling on snow or frozen ground. The training center has sixteen constructed sediment retention ponds maintained for erosion control and monitoring.

The YTC recognizes a need to evaluate erosion levels caused by land use, and quantify sediment movement against natural erosion rates. To address this need, YTC will determine natural erosion rates, monitor in-stream sediment concentrations, and plans to develop a model that allows comparison of current erosion with background rates (YTC, 2002). CRREL and NRCS are evaluating erosion rates within small watersheds that receive different types of use, and levels of precipitation. Measurements of erosion and deposition rates are collected in twelve sedimentation ponds constructed in 1984. Stream discharge, turbidity, temperature, and total suspended solids are also monitored at several locations within the YTC.

The hydrologic modeling proposed in this task addresses directly the Training Center's need to quantify erosion rates and sediment loading under alternative land uses. Many models are available to simulate watershed hydrology and sediment transport, ranging from relatively simple empirically based approaches to estimate runoff (e.g., the SCS Curve Number method) and long-term sediment yield (USLE, Wischmeier and Smith, 1978) to highly detailed, coupled runoff-sediment transport models such as MIKE-SHE (DHI, 1999) or WEPP (Lane and Nearing, 1989). The complex topography, meteorology, vegetation, soils, and land use patterns at YTC dictate the use of spatially distributed models to capture critical variability in runoff/erosion processes. The episodic nature of surface runoff and erosion in semiarid locations such as the YTC limits the opportunity for calibration, favoring physically based models with a limited number of input parameters. We have chosen to link two distributed, physically based models of intermediate complexity; the Distributed Hydrology Soil Vegetation Model (DHSVM) (Wigmosta et al., 1994; Stork et al., 1998; Wigmosta et al., 2001) will be used to simulate runoff production and the Hillslope Erosion Model (HEM) (Lane, et al., 1995; Lane et al., 2001) will be used to estimate sediment yield. These public-domain models were chosen for several reasons. Both models have been used extensively in land use analysis and they have been applied in semiarid regions. Their level of complexity is sufficient to capture dominant hydrologic processes at the YTC, let allow relatively easy transfer to the end user. Finally, Drs. Lane and Wigmosta lead the development of HEM and DHSVM, respectively, so any required modifications can be accomplished efficiently.

The Distributed Hydrology Soil Vegetation Model (DHSVM) is a physically based distributed parameter model that provides an integrated representation of watershed processes at the spatial scale described by digital elevation model (DEM) data. DHSVM has been utilized in a number of studies that focused on prediction of streamflow, evapotranspiration, and other surface energy and moisture fluxes (Wigmosta et al., 1994; Haddeland and Lettenmaier, 1995; Kenward and Lettenmaier, 1997; Wigmosta and

Lettenmaier, 1999; Westrick et al., 2000). The model has also been used to study the interactions between climate and hydrology (Wigmosta et al., 1995; Arola and Lettenmaier, 1996; Nijssen et al., 1997) and the potential impacts of climate change on water resources (Leung et al., 1996; Leung and Wigmosta, 1999; Wigmosta and Leung, 2001). Furthermore, the model has proven to be an important tool for assessment of the effects of forest management activities on watershed processes – especially floods (Storck et al., 1995, Lamarche and Lettenmaier, 1998; Storck et al., 1998; Storck et al., 1999; Bowling et al., 2000; Storck, 2000; Bowling and Lettenmaier, 2001; Wigmosta and Perkins, 2001). The model has been applied to the entire Yakima River basin. It is also being applied at a 30-m resolution to the Cold and Dry Creek watersheds adjacent to the YTC to model the relatively rare, short duration surface runoff events, generally associated with rain-on-snow conditions.

The modeled landscape is divided into computational grid cells centered on DEM nodes. This characterization of topography is used to model topographic controls on absorbed shortwave radiation, precipitation, air temperature, and downslope moisture redistribution. Vegetation characteristics and soil properties are assigned to each model grid cell and may vary spatially throughout the basin. In each grid cell the modeled land surface can be composed of a combination of vegetation and soil. At each time step, the model provides simultaneous solutions to energy and water balance equations for every grid cell in the watershed. Individual grid cells are hydrologically linked through surface and subsurface flow routing. The model predicts temporal and spatial changes in hydrologic properties such as snow cover and depth, soil moisture, ground saturation, soil temperature, subsurface water movement, surface runoff, and simplified 1-D channel flow.

The Hillslope Erosion Model (HEM - http://eisnr.tucson.ars.ag.gov/HillslopeErosionModel/) was developed by Dr. Leonard Lane and other scientists at United States Department of Agriculture - Agricultural Research Service (USDA-ARS) Southwest Watershed Research Center in Tucson, Arizona, USA. The HEM model is the product of over 30 years of hydrologic research in semiarid regions. HEM simulates rill and interrill erosion down a hillslope profile represented by a cascade of planer hillslope segments using an analytic solution to the coupled kinematic-wave and erosion (sediment continuity) equations for overland flow (Lane et al., 1995). The solution to the sediment continuity equation for the case of a constant and uniform rainfall excess is integrated through time (Shirley and Lane, 1978) to simulate the total sediment yield from the cascade for a given runoff event. The model requires a runoff volume per unit area and a soil-erodibility index for the entire hillslope. Input data for each of the individual segments are slope, length, percent vegetative canopy cover, and percent ground cover. The input data are used in parameter estimation procedures to compute the models depth-discharge coefficient, interrill erodibility, rill erodibility, and sediment transport coefficient. HEM calibration and validation studies were based on data from over 2000 plot events at experimental areas throughout the western U.S (Lane et al., 2001). The estimation procedures in HEM were developed from additional rainfall-simulator data collected in the western USA.

The Hillslope Erosion Model simulates erosion and transport associated with surface runoff generated by rainfall excess (= rainfall – infiltration), but does not simulate snow accumulation and melt. This limitation makes direct application of HEM (and most other erosion models) infeasible at the YTC site, where most erosion results from rapid snowmelt. DHSVM simulates surface runoff generated by 1) both rainfall and snowmelt excess, 2) direct rainfall/snowmelt on saturated soils (saturation overland flow), and 3) subsurface flow returning to the ground surface (return flow). The DHSVM simulated runoff volume per unit area for a given event will be input to HEM along with a soil erodibility index, initially taken from the YTC soils database.

The DHSVM-HEM linked modeling system will be applied to selected watersheds containing sedimentation ponds with measurements of erosion and deposition rates. The record will be split into calibration and validation periods. Key vegetation properties such as the type, leaf area index, albedo, canopy cover, and percent ground cover in each test watershed will be obtained from remote sensing as

described in Task 3. Segment lengths and slopes will be determined from DEM Terrain analysis. The extent of surface runoff simulated by DHSVM defines the spatial domain for the HEM analysis. Spatial patterns of simulated runoff volume will be used along with the vegetation, soils, and terrain information to define separate hillslope profiles for HEM. DHSVM-HEM simulated sediment yield will be compared with sedimentation pond measurements during the calibration period to define local HEM soil erodibility values and parameter estimation procedures. The model will then be run without adjustment during the during the validation period to evaluate model performance.

Task 5 - Demonstration, Technology Transfer, and Final Report

Throughout the duration of the project, efforts will be closely coordinated with YTC Public Works staff to insure products are compatible with YTC hardware and software systems and user-friendly. The demonstration of the adaptive management framework will be designed to address a sufficiently broad range of issues and complexity so as to fully exercise the functionality of the data management, process modeling and decision analysis components. The demonstration results and full explanation of the framework operations will be incorporated into the final report.

SUPPORTING TECHNICAL DATA

Table 1. PNNL Held Image Data for the YTC

Description	Format	Dates	Scale/Resolution	Notes
SPOT Panchromatic Images	Digital - Raster	1987-2001	10 meter pixels	3 images per year- early summer, mid-summer and early fall
SPOT Multispectral Images	Digital - Raster	1987-2001	20 meter pixels	1 image per year - early summer
Airphotos 1:12000	Analog	1983-2001	1:12000	Some color IR some true color
Use Map	Digital - Vector	1987-2001	1:24000	Change detection derived from SPOT Pan images and airphotos to track impact of training
Fire Map	Digital - Vector	1987-2001	1:24000	Outline of fire extent for the year
Vegetation Map	Digital - Vector	1999	1:24000	Field mapped existing and potential vegetation
Soil Map	Digital - Vector	1998	1:24000	Based on existing and new soils surveys
Tracked vehicle assessment	Analog	1996	N/A	Photos and notes
Wheeled vehicle assessment	Analog	2001	N/A	Photos and notes

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