Estimation of multi-season evapotranspiration

in relation to vegetation cover

for regions with rainy-winter/ dry-summer climate

Prepared by

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for

the **Upland Processes Science Advisory Group** of the Committee for Cooperative Monitoring, Evaluation, and Research (CMER), under Contract No. PSC 01-010 to the State of Washington Department of Natural Resources.

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Executive Summary

Report Title

Estimation of multi-season evapotranspiration in relation to vegetation cover for regions with rainy-winter/dry-summer climate. Prepared by Joan Sias for the Upland Processes Science Advisory Group of the Committee for Cooperative Monitoring, Evaluation, and Research (CMER), under Contract No. PSC-01-010 to the State of Washington Department of Natural Resources. October 2, 2003.

Project Context

Deep-seated landslides may deliver substantial volumes of sediment to streams, resulting in significant effects to fish habitat and water quality. Current forest practices rules require the highest level of regulatory oversight (i.e., a Class IV Special) for Forest Practices Applications that are at risk of activating or accelerating deep-seated landslides (WAC 222-16-050 (1)(d)(i)(C)). This rule has two problems. First, it is based on an unproven hypothesis that forest management can initiate deep-seated landslides. Second, no accepted methods exist for evaluating the physical effects of timber harvest on deep-seated landslides. This study addresses these problems. It was initiated in June of 2000 by the Upland Processes Scientific Advisory Group (UPSAG), a sub-group of the Cooperative Monitoring, Evaluation and Research Committee (CMER).

Physical Basis Of Canopy-Landslide Linkage

The hypothesized sequential links between vegetation changes and stability of deep-seated landslides are the following: Evapotranspiration is the sum of direct evaporation of water intercepted by vegetation canopies, and transpiration of soil water. Deforestation may lead to a decrease in evapotranspiration, and this, in turn, could increase the amount of water entering the sub-soil and the groundwater body. The resulting higher pore pressure could decrease in landslide stability. Many deep-seated landslides are sensitive to seasonal changes in soil moisture, but the degree to which soil moisture changes due to timber harvest are sufficient to activate or accelerate movement is unclear.

Objectives

The major objective of this project is to assess the change in evapotranspiration that may result from timber harvest, and the groundwater storage response to predicted evapotranspiration changes using an analytical model. (The direct stability responses of deep-seated landslides to these changes are not evaluated.) In doing so, this project refines a pre-existing hydrologic model that could support such regulatory determinations. The secondary objective of this project is to assess the potential for the model becoming a tool to assess the stability of deep-seated landslides on managed forest lands having a rain-dominated winter and droughty summer climate, as in the Puget Lowlands.

Study Design

The model combines the Penman-Monteith equation for estimating actual (as opposed to potential) evaporation and actual transpiration rates, the Rutter interception model for estimating canopy wetness status, and the Dupuit-Boussinesq horizontal aquifer model for estimating groundwater storage.

Model runs were performed for forest and evergreen shrub scenarios. Evergreen shrub was assumed to represent the regeneration phase (i.e., ~2-15 years following harvest) following fresh clearcut conditions. Parameters were assigned uncertainty intervals. Four runs (i.e., Forest high evapotranspiration, Forest low evapotranspiration, Shrub shrub high evapotranspiration, and Shrub low evapotranspiration) were performed to establish uncertainty intervals for model output for each of the two vegetation covers. Two versions of the model were developed; these were designated GAETP and GAETQ. GAETQ, which is a modified version of GAETP, contains an additional parameter EWP, which must be calibrated, whereas GAETP requires no calibration. EWP provides a simplistic way to address vertical advection, which is known to contribute significantly to evapotranspiration from tall, wet canopies during and after rainfall produced by stabily-stratified frontal weather systems , which are common in the Puget Sound Lowland in winter, Vertical advection is not adequately accounted for by GAETP. GAETP was used for the Shrub low evapotranspiration simulation; GAETQ was used for the other three evapotranspiration scenarios.

Major Conclusions

1. Winter evapotranspiration is a *potentially* non-negligible component of the annual water balance of an evergreen needle-leaf forest, and may be significant also for non-forest vegetation.

2. The uncertainty interval for the effect of forest-to-shrub conversion on winter and annual actual evapotranspiration (AET) is large, and ranges from no effect to a large decrease in annual AET.

3. The model results indicate that significant hydrologic effects *could* result from forest-to-shrub conversion, and that these effects are likely to be in a direction that is unfavorable for slope stability, and, conversely, *unlikely* to be in a direction that favors increased slope stability.

4. Use of the data humidity data from Seatac Airport leads to unrealistically high rates of winter AET for both vegetation covers. This result is not surprising, since humidity is quite sensitive to surface properties. Uncertainty about vapor pressure deficit and how it is affected by surface properties is a major source of uncertainty in the evapotranspiration simulations, and motivated the use of the modified version of the model (GAETQ).

5. The major sources of uncertainty in the evapotranspiration and groundwater storage simulations are: 1) the appropriate value to assign EWP in the forest simulation, and the appropriate model to use (GAETP or GAETQ) for shrub simulation, 2) the timing of the start of the groundwater recharge season in relation to vegetation cover, and 3) the value to assign to the parameter defining the rate of water table decline during periods of no-recharge.

6. Although some questions remain, data from daily-reporting NCDC stations can be used to run both versions of the model.

7. Research to address the major sources of uncertainty and to determine appropriate procedures for calibration of GAETQ is necessary for this model to be used as a screening tool. To avoid calibration, it may be necessary to have at-site measurements of near-surface relative humidity and windspeed, or to couple the hydrologic model to a multi-layered atmospheric boundary layer model.

Key Recommendations

Near-term research efforts should focus on making *empirical* determinations of the degree to which 1) cumulative winter evapotranspiration over forest is non-negligible, 2) vegetation conversion results in a significant decrease in cumulative winter evapotranspiration, and (3) the timing of start of the recharge season is changed after harvest. In addition, typical values of the aquifer parameter for different types of glacial-lacustrine deposits must be determined for use in the hydrogeological portion of the model. Further development of the model as a screening tool is not recommended until *after* the hypothetical linkage between forest practices and wet season groundwater storage is empirically substantiated. The proposed research should determinethe harvest-groundwater storage effect in several basins where glacial sediments and climate are the most conducive to such effect. If no effect appears in these basins, then conclusion can be drawn that no effect is likely to be found in *any* basin dominated by glacial sediments. The model may be useful for finding suitable sites for such experiments.

Table of Contents.

List of Tables.

List of Figures.

Acknowledgments

I am grateful to UPSAG for recommending to CMER that this project be funded, and to DNR for providing the funding. Several individuals have been helpful in significant ways. Several members of UPSAG provided helpful comments on earlier versions of the report. In particular, UPSAG members Paul Bakke, Julie Dieu, and Robert Palmquist undertook a thorough reading, and their comments lead to significant improvements in the clarity of the report. Mark Lobo helped with the derivation of equations [A-27] through [A-29], and suggested the method used to solve [A-33]. Linda Chiles and Ron Johnson provided contract services, and Venice Goetz and Robert Palmquist facilitated contract matters and interactions with UPSAG.

Elyn Humphreys (University of British Columbia) provided a copy of her master thesis, preprints of submitted journal manuscripts, and unpublished data. This information was of great value to this project, as were direct discussions with her. I greatly appreciate the time she took out of her busy schedule as a Ph.D. student to talk with me.

Dr. Jerry Franklin, director of the Wind River Canopy Crane Research Facility, kindly agreed to allow me to use micrometeorologic data from that site. Ken Bible (curate for WRCCRF) and Timothy Link (University of Idaho) provided helpful information about the data set.

Peer Review

This report was submitted to the Scientific Review Committee (SRC) as part of the formal report submission and acceptance process adopted by CMER. Included in Appendix C are the SRC transmittal documents (Appendix C1), the SRC reviews (Appendix C2), and the author's response to those reviews (Appendix C3). This section and Appendix C constitute the response to the SRC review considered most appropriate by the Upslope Processes Scientific Advisory Group (UPSAG).

SRC reviewers were highly critical of several of several important aspects of the study. As summarized by the editor (Appendix C.2.1) the SRC's concerns are:

- The use of the calibrated parameter EWP,
- Using meteorological data from Seatac Airport for calibration when other data sets are available,
- The assumption that winter evapotranspiration is non-negible, and
- The assumption of 100% relative humidity during winter.

UPSAG is of the opinion that these issues are fully addressed bu the author's response in Appendix C3. The only changes made in response to the SRC reviews appear in the Executive Summary. We encourage the reader to refer to Appendix C before judging the merits of the study or citing the study.

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A Overview and Summary.

Evapotranspiration is an important local control on groundwater recharge because it influences the timing and quantity of recharge to the groundwater system. This relationship has important implications for slope stability. Decreased evapotranspiration could lead to increased groundwater recharge, and, in turn, decreased stability of steep slopes. This paper primarily provides insights into evapotranspiration response to deforestation throughout an entire year, through application of a hydrologic simulation model called GAET—for groundwater and actual evapotranspiration and secondarily to groundwater response using a very simple aquifer model. This summary chapter

1. Provides background to the problem,
2. States research goals and objectives,
3. Describes the hydrologic model,
4. Summarizes key results and conclusions, and
5. Gives recommendations for future research.

This report contains an executive summary, four sections and two appendices. Section 2 presents the detailed model application results. Section 3 evaluates the feasibility of using daily data in place of hourly data to force the model. The bibliography appears as Section 4. Appendix A contains a detailed model description. Appendix B contains a categorized table of nomenclature. Section 2 and Appendix A are written in the format of scientific journal manuscripts, in fulfillment of a contract requirement. Appendix C contains the SRC reviews and aurthor's reponse.

A.1 Background.

Deep-seated landslides are common in the Puget Sound region (Gerstel et al., 1996; Shipman, 2001). These landslides move most often in winter. Deep-seated landslide activity and antecedent storm precipitation are highly correlated. The few available studies do not show that landslide activity is correlated to vegetation conversion. Koler (1992) found little empirical evidence to support or refute a hypothesized correlation. Keppeler et al. (1994) studied changes in pore pressure at the bedrock-soil interface before and after the harvesting of a forested hillslope. A dense network of monitoring instruments showed that pore pressures were elevated throughout the post-harvest monitoring period as compared to the unharvested control.

The complete understanding of the effects of vegetation removal on slope stability requires a better understanding of the difference in forest and non-forest evapotranspiration in all seasons of the year. Most empirical and theoretical treatments of forest evapotranspiration are relevant only to the 'growing season.' Winter interception studies with complete instrumentation and a high sampling density are few in number; the situation is even worse in the case of micrometeorologic experiments. Furthermore, multi-season interception and water balance studies that involve a forest and non-forest comparison are non-existent. Although several excellent review papers describe the effects of vegetation conversion on evapotranspiration, their data pertains to summer (Jarvis et al., 1976; McNaughton and Jarvis, 1983; Kelliher et al., 1993). Because of the limited number of studies and large site-to-site variation in important components of the forest and non-forest water budgets, the literature provides few insights for multi-season comparisons.

To overcome the lack of empirical data, Sias (1997) applied the Penman-Monteith (P-M) equation to simulate continuous, year-round actual evapotranspiration (**AET**) and groundwater recharge in the vicinity of the Hazel landslide adjacent to the Stillaguamish River, near Darrington, Washington. The simulation indicated that winter evapotranspiration may be a major component of the annual water budget for a forest, and would be considerably reduced by timber harvest. Depending on soil characteristics, decreased AET may result in increased groundwater recharge. Miller (1997) and Miller and Sias (1998) tested this possibility with a numerical groundwater simulation model, using the recharge predictions from Sias' model as input. These reports, which were not published and peer-reviewed, suggested that increased groundwater recharge would likely increase the potential for renewed movement of the Hazel landslide.

Subsequently, the Forests & Fish Agreement (USFWS et al., 1999) identified "groundwater recharge areas of glacial deep-seated landslides" as "high-risk" landforms. In March of 1999 the State of Washington adopted an emergency forest practices rule that requires geohydrological analysis for proposed timber harvesting on such landforms. The deep-seated landslide rule has two problems:

1. It is based on the results of an evapotranspiration model that has not been critically peer-reviewed, and the results have not been validated against empirical data.

2. No standardized, accepted methodology exists for the geohydrological analysis required under the rule.

A.2 Study goal and objectives.

The primary goal of this project is to answer—by means of hydrologic simulation modeling—the following questions about Puget Sound Lowland and western foothills of the Cascade Range below the transient snow zone:

1. What is the possible range of decrease in winter and annual AET that may result from timber harvest?

2. What range of changes in groundwater conditions might result from this decrease in AET?

The secondary goal of this project is to answer the question

> Can the model developed for this project be used to assess a site for the potential of significantly altered recharge and groundwater storage subsequent to deforestation?

The objectives of this study are as follows:

1. Update structure and parameterization of Sias' (1997) model, and add a function for simulating groundwater dynamics.
2. Recalculate the potential effects of vegetation conversion on seasonal and annual latent heat flux and groundwater dynamics, using hourly Surface Airways data from SeaTac international airport.
3. Compare the seasonal latent heat flux predictions for forest against recent empirical data collected over an old-growth forest in southwestern Washington.
4. Test consistency of output between
   a. Runs using Surface Airways data as input, and
   b. Runs using hourly input derived from daily precipitation (**P24**), daily minimum air temperature ($\mathbf{T_{min}}$), and daily maximum air temperature ($\mathbf{T_{max}}$).

Overall, these objectives address the two weaknesses of the emergency forest practices rule. The first two objectives address the primary goal. The third objective is an indirect validation exercise. The fourth objective addresses the secondary goal.

A.3 Summary of model design.

The model simulates evapotranspiration for contrasting vegetation types, water table fluctuations, and groundwater discharge for locations where precipitation occurs as rain. The model includes procedures for estimating the effects of vegetation conversion on meteorological variables. The model structure and meteorological inference procedures are fully described in **Appendix A**. The model is one-dimensional in the vertical axis. It simulates the latent heat flux for a homogenous patch of vegetated land surface. The patch is small enough that the latent heat flux at the upwind and downwind edges of the patch are not appreciably different.

For the present application, the model assumes that water may leave the system by only three routes:

1. Direct evaporation of moisture stored on vegetation,
2. Transpiration, and
3. Discharge from a groundwater aquifer.

These three components give the model its name "GAET" (**G**roundwater and **A**ctual **E**vapo**T**ranspiration). The following three equations are used to estimate each of the potential exit routes:

1. The Penman-Monteith model for wet-canopy evaporation and dry-canopy transpiration,
2. The Rutter interception model for determining canopy wetness status and net precipitation, and

3. The Dupuit-Boussinesq (D-B) baseflow equations for a horizontal, isotropic, and homogenous aquifer will fully penetrating stream.

The Penman-Monteith (P-M) equation was selected because of its strong physical basis, and because of its well-documented performance. When adequate forcing data are available, the P-M equation predicts latent heat flux that is similar to observed fluxes.

A.3.1 Novel features.

Except for a parameter '$\mathbf{t_{90}}$' that defines the hydraulic behavior of the groundwater aquifer, all parameters are vegetation-dependent. GAET has several novel features that allow the number of vegetation parameters to be kept to a minimum:

1. Aerodynamic conductance is expressed as the product of canopy drag coefficient and wind speed.
2. Canopy drag coefficient depends only on the surface roughness properties. Windspeed depends on measured windspeed and surface roughness properties at the anenometer and for the alternate vegetation cover.
3. Surface roughness properties (zero-plane displacement length and momentum roughness length) are determined as a fixed proportion (0.1 and 0.67, respectively) of canopy height.
4. The Rutter interception model drainage parameter is expressed as a function of canopy interception storage capacity, and the latter is a vegetation parameter.
5. The Tan et al. (1978) regression equations are used to model the dependence of canopy surface conductance on vapor pressure deficit and soil moisture tension. Separate regressions are provided for Douglas-fir and salal. The two sets of regressions are used for tall and short canopy, respectively.

Vegetation cover can have a strong influence on surface meteorological variables, and, consequently, also on latent heat flux. Rossby similarity theory is used to adjust measured windspeed for changes in surface roughness properties. The effect of vegetation conversion on outgoing shortwave radiation is addressed by making albedo a vegetation parameter. The effect of vegetation conversion on relative humidity and canopy surface temperature is explored through sensitivity analysis.

The output of the groundwater model is hourly storage and discharge time series for multiple values of τ_{90}. τ_{90} represents the amount of time required for the aquifer to lose ninety percent of its water content during periods of no-recharge; it is mathematically related to aquifer breadth and hydraulic conductivity. τ_{90} is certain to be highly dependent on site-specific geology and physical dimensions of the recharge area. Therefore it is treated as a sensitivity parameter: Simulations are performed for t_{90} ranging from 3 days to 180 days.

A.3.2 Simplifying assumptions.

The major simplifying assumptions in the present application of GAET are the following.

A1. All precipitation occurs as rain.

A2. With respect to the calculation of radiation, terrain is horizontal and is not subject to topographic shading.

A3. Available radiant energy is equal to net radiation, i.e., storage terms in the energy balance are neglected.

A4. The canopy-surface-resistance regression equations for Douglas fir apply to forests and those for salal apply to shrub. The regression equations, which are based on summer-time measurements, are assumed to apply in winter also.

A5. Surface infiltration capacity always exceeds the rate of precipitation, and surface runoff never occurs. All excess water in the root zone discharges to the groundwater body. Infiltration capacity at permeability horizons within the aquifer-soil column is never limiting to groundwater recharge, so that lateral subsurface flow of soil water never occurs.

A6. Depth to water table has no effect on soil moisture tension in the root zone, and capillary upflux does not occur.

A7. The steady-state water table profile is cosine-form.

A8. Discharge from the root zone arrives instantaneously at the water table and does not distort the steady-state profile. This assures that D-B aquifer theory is not violated.

A9. The D-B aquifer is isolated from the intermediate- and regional-scale groundwater system so that it receives no groundwater inflow other than local recharge.

A.3.3 Situational applicability.

This model, with all of the stated assumptions, is intended to be applicable for simulating groundwater recharge for a closed basin situated below the transient snow zone. The adjective ‘closed’ means that the basin is hydrologically-isolated from intermediate and regional-scale aquifers, which is to say that the groundwater supply to the basin is due strictly to local recharge. The assumptions of the groundwater simulation model are highly idealistic (as per Assumptions 8 and 9), and must be thought of as referring to the hydrostatic conditions in the recharge area hydraulically upslope from, but not within, a landslide body. The simulated water table dynamics are intended only to provide an indication of how recharge might affect ground water. They provide a basis for qualitatively interpreting the possible implications of altered evapotranspiration and recharge.

A.4 Model implementation.

With the exception of longwave radiation, all of the variables required for the P-M equation are available at hourly resolution in the TMY2 (Typical Meteorological Year 2) data set. This data set from the National Renewable Energy Laboratory provides a one-year time series, and is derived from multi-year Surface Airways data. The GAET simulations in this paper use TMY2 data from SeaTac Airport. To make the SeaTac data more representative of a Cascade foothills location, the winter precipitation of 24 inches was doubled. To modify precipitation without modifying radiative inputs is justified because, unlike precipitation, seasonal and annual radiation have a small interannual variability. The advantages of using TMY2 over the multi-year Surface Airways data are (1) TMY2 has no data gaps, and (2) managing model input and output and calculating run statistics is simplified with a single-year run. The major disadvantage of TMY2 is that it does not provide an opportunity for studying interannual variability.

The water year is set to April 1 through March 31, and initial root zone moisture content is set equal to capacity. This choice ensures that the simulated end-of-water year root zone storage is equal to the initial value. End-of-water year groundwater storage depends both on t_{90} and on the initial storage (i.e., the value assumed on April 1 of the simulation). To ensure that the initial and final values of groundwater storage match, the April 1 storage value for each value of t_{90} were manually adjusted.

A.5 Vegetation parameters.

Parameter sets are established for two contrasting vegetation covers: forest and shrub. Parameter values are listed in **Table 2-2**. The term 'forest' is used to mean evergreen needle-leaf forest. 'Shrub' is used to mean short evergreen vegetation, and includes sapling conifers, as well as broadleaf shrubs (e.g., salal). Except perhaps for the first winter following harvest, shrub is representative of the vegetation cover for at least the first decade following harvest (C. Veldhuissen, pers. commun.). In some locations, and depending on post-harvest site treatment, it may be more reasonable to assume deciduous cover. This possibility is not modeled here, since it is probably a less common situation.

For most of the model vegetation parameters, the correct value for the parameter is unknown. Therefore, vegetation parameters have uncertainty associated with them. To address parameter uncertainty, the parameter set for each vegetation cover consists of an upper- and lower-boundary value. The parameters are defined so that the upper-boundary value corresponds to high evapotranspiration (low recharge) potential, and the lower-boundary value corresponds to low evapotranspiration (high recharge) potential. The boundary values represent the largest and smallest value that the parameter is likely to take.

A.6 Methods.

A.6.1 Quantification of predictive uncertainty.

The questions posed in "Study Goals and Objectives" ask if differences in groundwater recharge and storage result from forest harvesting. The model does not provide a straightforward answer to this question because of the range of possible values (uncertainty) for each parameter. The strategy used to assess the question involves calculation of uncertainity and then comparison of uncertainity overlap. Uncertainity was assessed by first running the model for each vegetation cover to calculate results with all parameters their first at their upper-bound value and second at their lower-bound value. The uncertainty intervals for AET and groundwater storage under each vegetation cover are defined by these two sets of results.

The greater the extent to which uncertainty intervals for AET and groundwater storage for the two vegetation covers are *non*-overlapping, the more strongly do the model results provide theoretical evidence that AET and storage will change significantly after timber harvest. As the overlap of the uncertainty intervals increases, the possibility of no significant hydrologic change increases.

A.6.2 Validation.

The purpose of Objective 3 is to validate the model. Validation consists of comparing model results to actual observations. Validation results may corroborate or refute the model. Whether the validation test provides strong or weak evidence in favor of or against the model depends on how the test is designed, and how well the model predictions compare to observations. Strong corroboration of the model gives it credibility. Objective 3 refers to data collected at a University of Washington’s Wind River Canopy Crane Research Facility in southwestern Washington. This crane is located in the T.T. Munger old-growth forest reserve. The crane is situated in a 500 year-old forest stand. Data collection began in 1997. The data set includes all the meteorological variables required for the P-M calculation, as well as throughfall data for validating net precipitation (i.e., precipitation less predicted evapotranspiration). It was determined that this data set contained too many lengthy gaps to be useful for validation.

A second validation data set was later identified. The data set includes micrometeorologic variables and latent heat flux over a 50 year-old stand of Douglas-fir. For reasons that will not be stated here, it is likely that latent fluxes over a 50 year-old stand of Douglas-fir are more like those over old-growth forest than over a shrub cover. The meteorological instruments are positioned on a tower, and the tower was placed in a location that was deemed likely to be free of horizontal advection. The data set is described in detail later in this section of the report.

The validation test consists of comparing measured and modeled values of the ratio of actual evapotranspiration (**AET**) to available radiation (**Q***). The comparison is made on a seasonal basis, with emphasis on winter results. The model was run in advection-free model (i.e., by setting relative humidity to 1.0 at all time steps), and all parameters were set to the forest HIGH_ET values. (Little difference in the forest HIGH_ET and LOW_ET simulation results were noted).

This is an indirect validation test, since the model was run with data from SeaTac, instead of from the canopy crane. The reason for comparing [AET/Q*] rather than absolute values of AET is to normalize for differences in climate. I make the assumption that the seasonal ratios of [AET/Q*] observed at Vancouver Island are not unique to this site. §2.8 of this report discusses whether this assumption is justified.

A.6.3 Evaluation of model performance with alternate data source.

The TMY2 data set is derived from National Weather Service Surface Airways (SA) data sets. These are available at a limited number of locations. In Washington there are nine SA stations; of these, all but one (SeaTac) lacks at least one of the meteorological variables required by the Penman-Monteith equation. Objective 4b refers to data provided by National Climate Data Center (NCDC) stations. NCDC stations are more numerous than SA stations: The NCDC data base for the state of Washington contains 392 stations, 153 of which were active as of December 31, 1999. For assessing regional variability of evapotranspiration and hydrologic effects of vegetation conversion and for routine application of the model the ability to run the model with NCDC data instead of Surface Airways data is highly desirable. The purpose of Objective 4 is to determine whether the model will give valid results when NCDC daily data (i.e., P24, T_{min}, and T_{max}) are used as the primary model input, in place of the hourly TMY2 data.

The procedure for carrying out the NCDC evaluation is as follows.

1. The TMY2 hourly time series of precipitation is aggregated to 24-hour totals, (midnight-to-midnight). The 24-hour precipitation total is assumed to be uniformly distributed over the day.
2. The daily time series of T_{min} and T_{max} are extracted from the hourly air temperature time series. A sine-form interpolation is applied to estimate hourly air temperature record from the T_{min} and T_{max} time series. For this interpolation, T_{min} and T_{max} are assumed to be the actual air temperature at 6 am and 1 pm, respectively.
3. Hourly net radiation is calculated as

$$Q_{(t)}=(1-\alpha)0.3\ K_{ex(t)} \text{ when } P24_{(t)} > 0$$

$$Q_{(t)}=(1-\alpha)0.5\ K_{ex(t)} \text{ when } P24_{(t)} = 0,$$

where K_{ex} and K_{in} are the extraterrestrial and earth-surface values for incoming global horizontal shortwave radiation. This estimate for net radiation neglects longwave radiation. The parameters 0.5 and 0.3 were estimated from SeaTac TMY2. No effort was made to estimate relative humidity from the NCDC variables. A relative humidity estimate was not required since advection is addressed as a sensitivity analysis.

A.7 Validation Results.

A.7.1 Summary of observational data.

Two recent papers describe micrometeorological measurements for a 50 year-old Douglas-fir stand on Vancouver Island, B.C. (Humphrey, 1999, Humphrey et al., 2001). These papers provide valuable information for *qualitative* validation. The most relevant results are

1. cumulative AET for each of three winters matches the evaporative equivalent of cumulative Q* for the same period; equivalently, the ratio of cumulative AET to cumulative Q* is 1.0 for each of the three winters;
2. half of winter AET occurs at night, as compared to 10 percent in summer;
3. interannual variability of winter season AET and Q* is minimal, despite large interannual variability of seasonal precipitation total; and
4. summer AET for each of two seasons of measurements is 318 mm (i.e., for April-September of 1998 and 1999), and this is only about half of the evaporative equivalent of the seasonal available radiation supply.

A.7.2 Comparison of measurements and predictions; model modification.

The comparison of model results to the Vancouver Island observations produced mixed results:

1. GAET appears to give valid results for dry season: The simulated summer AET at SeaTac is 303 mm—very close to the measured dry season AET of 318 mm at the Vancouver Island study site.
2. GAET's predictions for advection-free winter conditions agree poorly with the Vancouver Island observations: GAET predicts that the winter ratio of AET/Q* is 0.3. Furthermore, the model predicts that nighttime latent heat flux is zero throughout the year.

In order to more closely emulate the Vancouver Island observations, a potential evaporation rate parameter (**EWP**) was substituted for the source term of the P-M equation. EWP is used only in winter. The modified model retains P-M for summer latent heat flux calculations. The original and modified models are designated **GAETP** and **GAETQ**, respectively.

It was decided to calibrate EWP so that wet-season latent heat flux equates with Q* in an advection-free run. This has the implication that, according to GAETQ, Q* is a lower-limit estimate for seasonal total latent heat flux for forest and non-forest, and that winter latent heat flux dependence on vegetation cover is determined entirely by albedo.

It is not known whether EWP should be used in the case of shrub. In order to fully admit this source of uncertainty, it was decided to use GAETQ for Shrub HIGH_ET, and GAETP for Shrub LOW_ET.

This represents an additional model assumption:

A10. Shrub LOW_ET is modeled with GAETP. Forest HIGH_ET, Forest LOW_ET, and Shrub HIGH_ET are modeled with GAETQ, and, for these three parameter sets, winter latent heat flux in absence of advection equates with net radiation.

A.8 Major Results.

It must be emphasized that the results of the evapotranspiration analysis cannot be assumed to apply to locations other than those having a climate characterized by mild, wet winters and droughty summers.

A.8.1 The role of horizontal advection.

1. The model predicts that winter latent heat flux is very sensitive to relative humidity, regardless of vegetation cover. (Relative humidity less than 100 percent and non-zero wind speed are both necessary for advectively-forced latent heat flux to occur.) Using measured relative humidity causes winter AET to increase by four-fold (from 246 to 1074 mm, as shown in Table 2-6), so that 80 percent of winter gross precipitation is lost as evapotranspiration.
2. Summer AET is not as sensitive to relative humidity as is winter AET. Summer AET increases by at most two-fold due to advection (i.e., from 275 to 551 mm). Only weak advection is required for summer AET to be forced close to its maximum potential value.

The interception loss (**IL**) rate of 80 percent indicated in the first result is unrealistic: Numerous interception loss studies have been reported in the literature. There are none which show forest IL exceeding more than about 1/3 of gross precipitation. Most studies show IL rates of less than 20 percent.

The second result is due to the fact that moisture supply provides a strong limitation to summer AET: Simulated summer AET cannot exceed the sum of root zone available water capacity (e.g., 350 mm and 150 mm in the Forest HIGH_ET and Shrub LOW_ET cases, respectively) and summer precipitation total (i.e., 205 mm in all cases). Maximum summer AET ranges from 355 in the Shrub LOW_ET case to 555 mm in the Forest HIGH_ET case.

Based on these results, it was decided for the remaining assessments to assume no horizontalnadvection in winter, and moderate advection in summer. The moderate-advection scenario assumes that during-storm and between-storm relative humidity is 100 percent and 95 percent, respectively. It happens that the moderate and strong advection scenarios give similar results for summer AET.

A.8.2 Vegetation-conversion effects on water balance and soil moisture patterns.

1. <u>The uncertainty intervals for seasonal and annual forest AET are small</u> (**Table 1-1A**, **Figure 1-1**).
2. <u>The uncertainty interval for shrub AET is large</u> (**Table 1-1A**, **Figure 1-1**). Most of the large uncertainty in the simulated latent heat flux for shrub is due to the fact that the Shrub LOW_ET and HIGH_ET simulations use different versions of the model. The Shrub LOW_ET simulations uses GAETP, and the Shrub HIGH_ET simulation uses GAETQ. GAETP uses the P-M equation to calculate winter ET. GAETQ used a parameter EWP which is calibrated so that winter ET equates with winter net radiation. Both versions of the model is the P-M equation in summer.

3. The uncertainty interval for the *change* in latent heat flux ranges from little-or-no-change to a large decrease (**Figure 1-2**). The large change occurs for the comparison of the Forest HIGH_ET simulation with the Shub LOW_ET simulation. The Shrub LOW_ET parameter set gives much lower winter and summer latent heat fluxes than both of the forest parameter sets: Winter, summer, and annual AET decrease by about 70 percent, 45 percent, and 65 percent, respectively, when the LOW_ET shrub parameters are used in place of forest HIGH_ET parameters.

4. The uncertainty interval for the *change* in winter groundwater storage ranges from little-or-no-change to a large increase. **Figure 1-3** compares the groundwater simulations obtained with the Forest HIGH_ET and Shrub LOW_ET parameter sets. For both covers, groundwater storage declines fairly steadily through the dry season; by end of dry season, groundwater storage is fairly similar for the two covers. Differences in groundwater storage between the two covers are established early in the wet season, in response to differences in timing of full wetting-up of the root zone soil moisture compartment. The winter storage contrast is smaller when results for the Forest LOW_ET parameter set are compared to the Shrub HIGH_ET results.

5. The change in winter groundwater storage resulting from forest-to-shrub conversion is strongly dependent on t_{90} (**Figure 1-4**). As t_{90} increases (representing a decrease in aquifer transmissivity), the storage difference (i.e., shrub minus forest) becomes more pronounced and more persistent. For example, for t_{90}=180 days, storage difference remains above 70 mm throughout the wet season, and remains above 100 mm from late-October to late November. For low values of t_{90}, storage for shrub remains substantially elevated above that of forest for a much shorter period. For example, for t_{90}= 3 days, a storage difference is nearly zero throughout winter except for about 10 days in the early wet season.

A.8.3 Sensitivity analysis.

Table 1-2 asseses the contribution of the vegetation parameters and two meteorological variables to the uncertainty in model output. The upper boundary and lower boundary values correspond to the Forest HIGH_ET and Shrub LOW_ET simulations, respectively. The 'seasonal' columns in Table 1-1 refer to both cumulative AET and to groundwater storage. Using GAETQ for Forest High_ ET and GAETP for Shrub LOW_ET explains most of the uncertainty in the predicted hydrologic effects of forest-to-shrub conversion, as well as most of the uncertainty in the results of the shrub simulations. As detailed in the following list, one meteorological variable and three vegetation parameters explain most of the remaining uncertainty. These are between-storm relative humidity, maximum canopy stomatal resistance, albedo, and root zone moisture storage capacity. The contribution of t_{90} to uncertainty in groundwater storage was already described, and will not be reiterated here.

1. Interception loss (which is mainly limited to winter) is more strongly influenced by albedo than any other vegetation parameter.

2. It is notable that a large uncertainty interval for canopy storage capacity (Cx) has little effect on the net precipitation and interception loss. Increasing Cx from 1.0 to 3.0 results in slightly reduced during-event drainage rates and slightly lower storm-total interception loss. These effects are offset by higher between-storm interception loss.

3. Among the several parameters of the canopy surface resistance model (i.e., Q_sm, g_{st}m, and LAI), only g_{st}m makes a significant contribution to uncertainty in cumulative transpiration, and this influence is apparent only in the advection-free simulations.

4. In advection-positive simulations, the major determinants of summer cumulative AET are RZx and summer cumulative precipitation.

5. Among all vegetation parameters, RZx has the strongest influence on end-of-dry season groundwater storage and timing of the start of the groundwater recharge season. Through these effects, RZx contributes to uncertainty in the probability distribution for groundwater storage and annual peak storage.

6. Horizontal advection will be zero unless windspeed is non-zero *and* relative humidity is less than 1.0. Both of these meteorological variables have uncertainty associated with them. Relative humidity is treated as a sensitivity variable. Windspeed over forest and shrub is estimated from windspeed measured at SeaTac airport and through application of the transvaluation scheme described in **§A.4.4**. It turns out that uncertainty in windspeed is much less significant than uncertainty associated with RH_{BS}. Table 1-2 shows no influence of RH_{BS} on winter AET. The lack of influence in winter is due to the fact that it was decided to set RH_{BS} to zero in winter.

A.8.4 NCDC evaluation.

The following statements refer to procedures for estimating hourly precipitation, net radiation, and air temperature from P24, T_{min}, and T_{max}. These procedures are described in Section 3.

1. Using estimated net radiation in place of TMY2 hourly data had no appreciable adverse effect on model output.
2. Model results were not affected by using interpolated air temperature (i.e., from T_{min} and T_{max}) in place of TMY2 hourly air temperature.
3. Latent heat flux predictions are quite sensitive to how 24-hour cumulative precipitation is distributed over each 24-hour period. A solution to this problem is proposed, but this solution is only valid for use with the GAETQ version of the model.

A.8.5 Comparison to results from the Hazel landslide analysis (Sias, 1997).

Results from Sias (1997) are summarized in **Table 1-3**. It is most relevant to compare winter latent heat flux results, since—as already discussed—winter latent heat flux has more effect on winter groundwater storage than does summer latent heat flux. In this paper forest winter latent heat flux is estimated to be 241±5 mm. The corresponding result from Sias (1997) is 606±77mm. The uncertainty interval for the *change* in winter latent heat flux is -105±100 mm in this paper, and -573±291 mm in Sias (1997). The differences in results are explained as follows:

1. In Sias (1997), forest was being contrasted to deciduous cover. This paper compares forest to shrub. Forest-to-shrub conversion should produce a smaller change in winter latent heat flux than forest-to-deciduous conversion.
2. Sias (1997) allowed horizontal advection to occur throughout the year, not just in summer, as in the present study. Allowing winter advection causes forest latent heat flux to increase dramatically, bringing GAET's forest results more in line with Sias (1997).
3. Sias' (1997) analysis was carried out using NCDC climate date from Darrington, Washington. The winter rainfall total there averages about 1500 mm, or about 300 mm greater than in the present application. This difference in winter precipitation may partially explain the higher winter latent heat flux obtained in the 1997 report.

A.9 Major conclusions.

As explained in §1.2, the goal of this project is to answer the following three questions.

1. What is the possible range of decrease in winter and annual AET that may result from timber harvest?
2. What range of changes in groundwater conditions might result from this decrease in AET?
3. Can the model developed for this project be used to assess a site for the potential of significantly altered recharge and groundwater storage subsequent to deforestation?

The first question has already been answered in §1.8.2. The second question is answered in the following section (§1.9.1). The third question is addressed in §1.10.1.

A.9.1 Answers to fundamental questions.

This project was intended to address four fundamental questions. These questions appear in the proposal and the contract. Although this study does not answer every question fully, it does provide the following insights.

Question #1. <u>Does forest harvest produce a statistically significant change in groundwater recharge?</u>

Because groundwater recharge is minimal in summer, the change in annual groundwater recharge is approximately equal to the *negative* of the change in winter AET. Whether vegetetation conversion causes a change in recharge depends in part on whether winter advection is significant. The uncertainty interval for the change in winter AET in absence of significant advection ranges from +6 mm (in the Forest LOW_ET/Shrub HIGH_ET comparison) to –205 mm (in the Forest HIGH_ET/Shrub LOW_ET comparison). *As winter advection increases, the change in groundwater recharge decreases.*

Question #2. <u>How long do changes in groundwater recharge persist?</u>

Changes in groundwater recharge are evident only in the winter. Differences in recharge rate under forest and shrub are greatest in the early autumn. Regardless of cover, seasonal groundwater recharge does not resume in the autumn until moisture content in the root zone has been restored to field capacity. Largely because the rooting depth under short vegetation is assumed to be less than under tall vegetation, the timing of the start of the groundwater recharge season is about 20 days later under forest than under shrub. After this time, differences in recharge rate persist throughout the wet season, but are smaller in magnitude. The difference in timing of onset of the groundwater recharge season is responsible for most of the forest-vs-shrub contrast in groundwater recharge and groundwater storage.

Question #3. Is there a change in the probability distribution for groundwater level and antecedent moisture conditions?

A major source of uncertainty is t_{90}. Depending on t_{90}, the model predicts that forest-to-shrub conversion could result in little-or-no change to major changes in the groundwater storage probability distribution. For small t_{90}—which corresponds to a highly conductive, rapidly-responding aquifer—the groundwater storage shows little sensitivity for vegetation cover. For large t_{90}, groundwater storage is markedly higher throughout the wet season due to forest-to-shrub conversion.

Question #4. Are groundwater recharge and subsurface moisture conditions likely to be changed by harvest to such an extent that increased risk of landslide response (initiation of or acceleration of movement) is incurred as a result of forest harvest?

This question is beyond the scope of the study. Included in the model description is an explanation of how one could derive the water table profile for a given state value of groundwater storage. From this one could ultimately infer a pore pressure distribution along a potential slip face. Such a calculation was not performed for purpose of this project, as the emphasis was limited to hydrologic assessments.

A.9.2 Major sources of uncertainty.

These are listed in order of decreasing importance. The first two statements refer to major gaps in empirical knowledge; the remaining statements address modeling issues.

1. It is not known whether actual fluxes over forest and non-forest in Puget Sound Lowland and similar environments fall within the ranges predicted in this report.
2. There is a large uncertainty associated with the predicted timing of the start of the groundwater recharge season. Accurate estimation of this variable is important, since it strongly influences the persistence of vegetation-dependent differences in groundwater storage throughout winter, particularly at high values of t_{90}.
3. It is not known whether GAETP or GAETQ should be used for modeling winter AET in the case of shrub, which is to say that it is not known whether vertical advection can occur over short vegetation to the same extent that it occurs over tall vegetation.

4. It is not known whether Humphrey and co-workers' observation that cumulative winter AET equates with cumulative winter net radiation is applicable to locations other than the experimental forest they are studying. Therefore, it is not known whether EWP should be calibrated to achieve this balance in all applications GAETQ. If this source of uncertainty had been addressed by the simulations, then the uncertainty intervals for Forest AET, recharge, and groundwater storage would be larger than indicated in Section 1.8.2, Table 1-2, and Figures 1-1 through 1-4. On the other hand, this source of uncertainty does *not* cast doubt on the conclusion that shrub ET is *unlikely to exceed* forest ET.

5. It is not known whether it is justified to assume horizontal advection is zero in winter.

6. Reasonable upper and lower limits for the aquifer parameter t_{90} are not known.

A.10 Research recommendations.

A.10.1 General comments.

Further development of the model for routine application is not warranted at this time. Immediate research should focus first on empirical tests of vegetation-conversion effects on winter latent heat flux and timing of start of groundwater recharge season, and secondly on model validation. Longer-term research should focus on determining the site-specific characteristics for which vegetation-related differences in latent heat flux are likely to lead to higher winter water table elevations.

A.10.2 Specific recommendations.

The first three recommendations listed here would help to establish empirically-based answers to the main questions posed for the research (*1. What is the possible range of decrease in winter and annual AET that may result from timber harvest? 2. What range of changes in groundwater conditions might result from this decrease in AET?*). The last three recommendations are relevant to development of the model as a screening tool.

1. Analyze streamflow and precipitation data to determine whether winter AET is significant within this region. (If change in subsurface storage is neglected, then AET is equal to precipitation minus streamflow.) Paired catchment data would be useful for this purpose, and also for testing whether winter and/or summer AET differ significantly for forest and clearcut watersheds. Julia Jones and co-workers have recently undertaken research in this vein (Julia Jones, pers. commun.).

2. Determine whether timber harvest results in a significant change in the timing of the start of the groundwater recharge season. A literature review may be sufficient to establish an empirical answer to this question.

3. Develop a method for estimating t_{90} from site-specific hydrologic data. Establish an empirical uncertainty interval for t_{90} for representative sites. Determine whether it would

be rare for t_{90} to be high enough for vegetation-conversion to result in increased probability of slope instability.

4. Determine whether vertical advection does or does not occur over non-forest in winter, at similar rates as over forest. Ongoing micrometeorological research by Elyn Humphreys and co-workers at forested and clearcut sites on Vancouver Island may help to settle this question. Application of a numerical atmospheric boundary layer model, such as described by De Bruin and Jacobs (1989), may also be helpful.
5. Determine under what site conditions, if any, horizontal advection is likely to cause significantly-elevated cumulative winter AET.
6. Determine whether it is justified to assume for any location that winter AET over forest equates with seasonal net radiation, and furthermore, whether or not this equivalence is also obtained for non-forest vegetation. The answer to the second part of this question will help to establish whether evergreen shrub, deciduous cover, and clearcut should be modeled with the GAETP or GAETQ version of the model.

Table A-1. **Uncertainty interval for change in seasonal and annual evapotranspiration, due to forest-to-shrub conversion.**[a]

A. No advection.

	Forest LOW_ET			Shrub HIGH_ET			Change in AET (LOW)		
	SUMMER	WINTER	ANNUAL	SUMMER	WINTER	ANNUAL	SUMMER	WINTER	ANNUAL
IL[b]	26	195	221	26	195	221	0	0	
TR	228	41	269	225	47	272	-3	+6	
IL+TR	254	236	490	251	242	492	-3	+6	**+3**
	Forest HIGH_ET			**Shrub LOW_ET**			**Change in ET (HIGH)**		
	SUMMER	WINTER	ANNUAL	SUMMER	WINTER	ANNUAL	SUMMER	WINTER	ANNUAL
IL	26	200	226	21	19	40	-5	-181	
TR	249	46	295	126	22	148	-123	-24	
IL+TR	275	246	521	147	41	188	-128	-205	**-333**

B. No advection in winter; moderate advection in summer.

	Forest LOW_ET+			Shrub HIGH_ET+			Change in AET (LOW+)		
	SUMMER	WINTER	ANNUAL	SUMMER	WINTER	ANNUAL	SUMMER	WINTER	ANNUAL
IL[b]	106	195	221	95	195	290	-11	0	
TR	445	41	269	355	47	402	-90	+6	
IL+TR	551	236	490	450	242	692	-101	+6	**-95**
	Forest HIGH_ET+			Shrub LOW_ET+			Change in AET (HIGH+)		
	SUMMER	WINTER	ANNUAL	SUMMER	WINTER	ANNUAL	SUMMER	WINTER	ANNUAL
IL	106	200	306	92	19	111	-14	-181	
TR	445	46	491	242	22	264	-203	-24	
IL+TR	551	246	797	334	41	375	-227	-205	**-432**

[a]All values in mm.

[b]IL: interception loss; TR: transpiration.

Table A-2. **Parameter influence matrix.**

Parameters and meteorological variables					**Influence**					
		Bounds[a]			Seasonal[b]		Flux component		Forcing term	
Name	Units	Lower	Upper	Description	Winter	Summer	Evap.	Trans.	Rad.	Adv.
Model Version	n/a	'P'	'Q'	GAETP and GAETQ differ in the manner of calculating winter wet-canopy evaporation. Using GAETQ for Shrub High_ ET and GAETP for Shrub LOW_ET explains most of the uncertainty in the shrub predictions.	**H**	n/a	x		x	
EWP	mm d^{-1}	n/a	n/a	Wet canopy potential evaporation rate parameter. This is used only in GAETQ, and is calibrated so that winter latent heat flux matches Q*.	**H**[c]	n/a	x		x	
α	[1]	.20	.08	Net fraction of incoming shortwave radiation that is reflected back to the outer atmosphere. High albedo corresponds to lower PET (i.e., lower bound albedo > upper bound albedo)	**M**	L	x	x	x	
Cx	mm	0.5	3	Canopy storage capacity. Drainage of water from the surface of a wet canopy is negligible except when storage exceeds Cx.	L	L	x		x	x
$Q_S m$	W m^{-2}	70	35	Minimum incoming shortwave radiation required to induce opening of stomata.	L	L		x	x	x
$g_{st}m$	mm s^{-1}	0.1	0.3	Cuticular conductance. This is equal to minimum canopy *surface* conductance ($g_S m$) when LAI=1.0. (See also entry for LAI).	L	**M**		x	x	x
LAI	[1]	2	8	One-sided leaf area index. LAI influences canopy surface conductance, and therefore, transpiration. Canopy surface conductance is also influenced by soil water status.	L	L		x	x	x
RZx	mm	150	350	Maximum quantity of plant-available water in well-drained soil. Strongly influences the timing of the start of the groundwater recharge season.	**H**	**H**		x	n/a	n/a
H_c	m	2	40	Effective canopy height. This determines surface roughness parameters. Canopy height and windspeed determine aerodynamic conductance to vapor transport.	L	L	x	x	x	x
RH_{BS}	[1]	1.0	M	Relative humidity during hours of zero precipitation. RH_{BS}=1.0 represents the advection-free case. 'M' indicates use of measured value from the SeaTac TMY2 data set.	L[c]	**H**	x	x		x
$U_2(t)$		n/a	n/a	Windspeed at 2 m above the canopy. $U_2(t)$ over forest and shrub is estimated from surface roughness parameters and measured windspeed. There is uncertainty associated with windspeed due to uncertainty about surface roughness parameters at the SeaTac anenometer.	L	L	x	x	x	x

[a]Upper and lower bound refers to potential evapotranspiration (PET), and to Forest HIGH_ET and Shrub LOW_ET assigned values, respectively. All vegetation and sensitivity parameters are listed in Appendix B. The following vegetation and sensitivity parameters are given the same value for all runs, and therefore are not listed in this table: Canopy gap fraction (GF), infiltration fraction (INF) and D_F/D_G are set to unity; $\ln(\mathbf{z}_{oM}/\mathbf{z}_{oV})$ is assigned a value of 2.0; wetting-front vertical travel time (T_v) and the four temperature differential parameters (all of which are listed as sensitivity variables in Appendix B) are set to zero.

[b]Effect on AET (evaporation plus transpiration) and groundwater storage: n/a, H, M, and L represent not applicable, strong, moderate, and little-or-no influence, respectively.

[c]For discussion of EWP influence, see list item 4 in §1.9.2; for discussion of RH_{BS} winter influence, see list item 6 in §1.8.3

Table A-3. **Uncertainty interval for change in seasonal and annual evapotranspiration, due to forest-to-clearcut conversion: Results from Sias (1997).[a]**

	Forest LOW_ET			Clearcut HIGH_ET			Change in AET (LOW)		
	SUMMER	WINTER	ANNUAL	SUMMER	WINTER	ANNUAL	SUMMER	WINTER	ANNUAL
IL	74	238	312	50	87	137	-24	-151	
TR	160	291	451	344	0	344	184	-291	
IL+TR	234	529	763	394	87	481	160	-442	**-282**
	Forest HIGH_ET			**Clearcut LOW_ET**			**Change in AET (HIGH)**		
	SUMMER	WINTER	ANNUAL	SUMMER	WINTER	ANNUAL	SUMMER	WINTER	ANNUAL
IL	133	419	552	50	74	124	-83	-345	
TR	359	264	623	186	0	186	-173	-264	
IL+TR	492	683	1175	236	74	310	-256	-609	**-865**

[a]Advection is allowed in both seasons. Relative humidity is estimated from air temperature data.

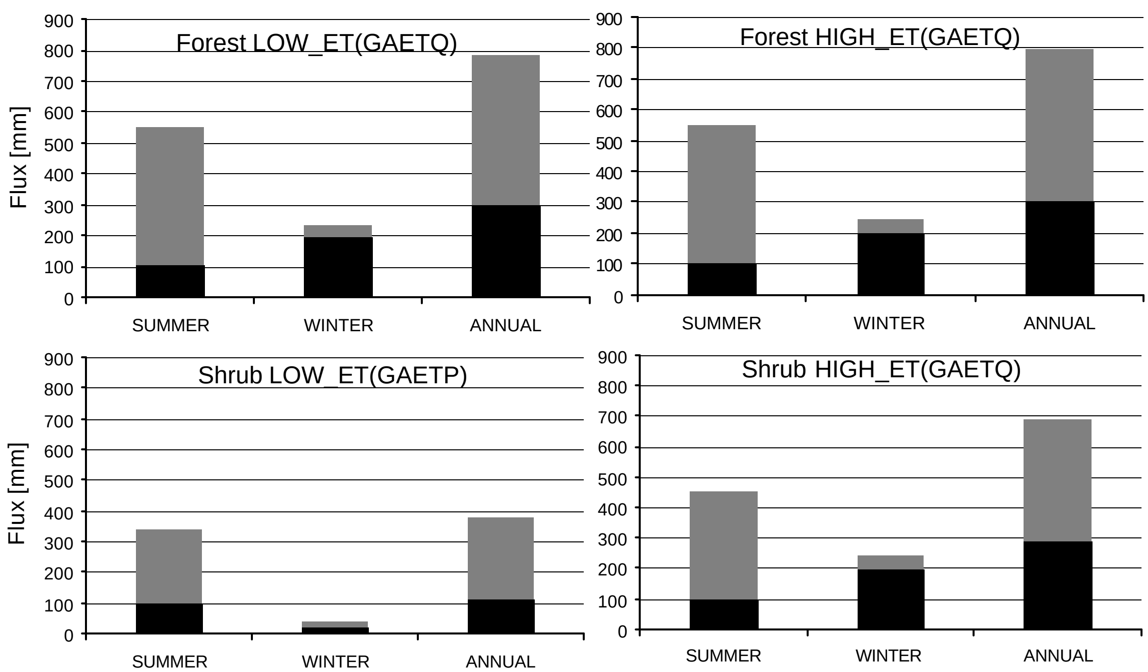

Figure A-1. **Seasonal and annual water balance: Interception loss (black) and transpiration (gray). These simulations are advection-free in winter and allow moderate advection in summer, as in**

Table 1-1B. Vegetation scenario and model version are indicated in each panel. The moderate- and strong-advection scenarios produce similar results in summer.

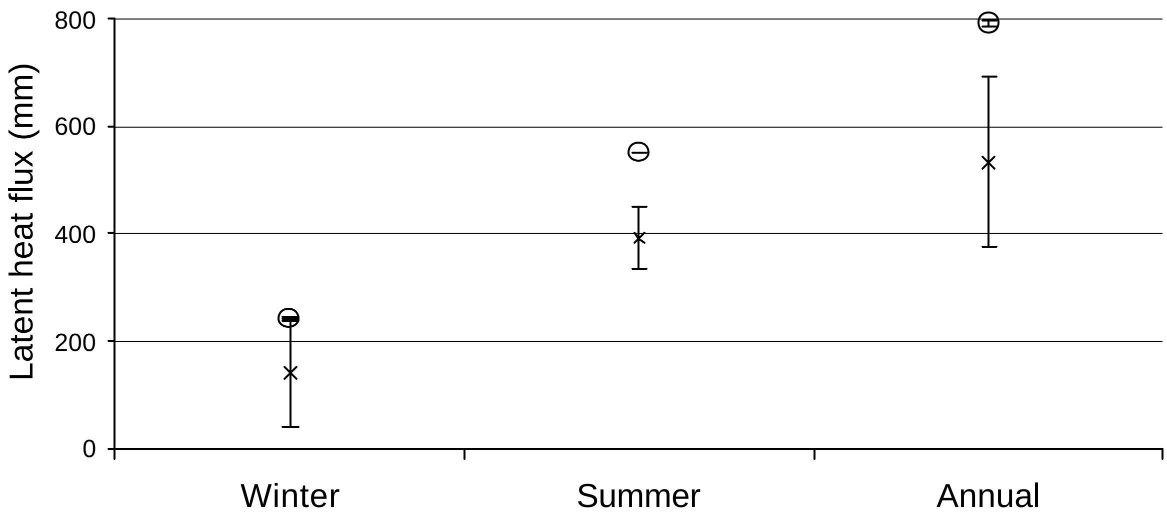

Figure A-2. Uncertainty intervals for seasonal and annual latent heat flux: Forest (circle) and shrub (x). Winter results are for advection-free simulation. Summer results are for moderate-advection scenario.

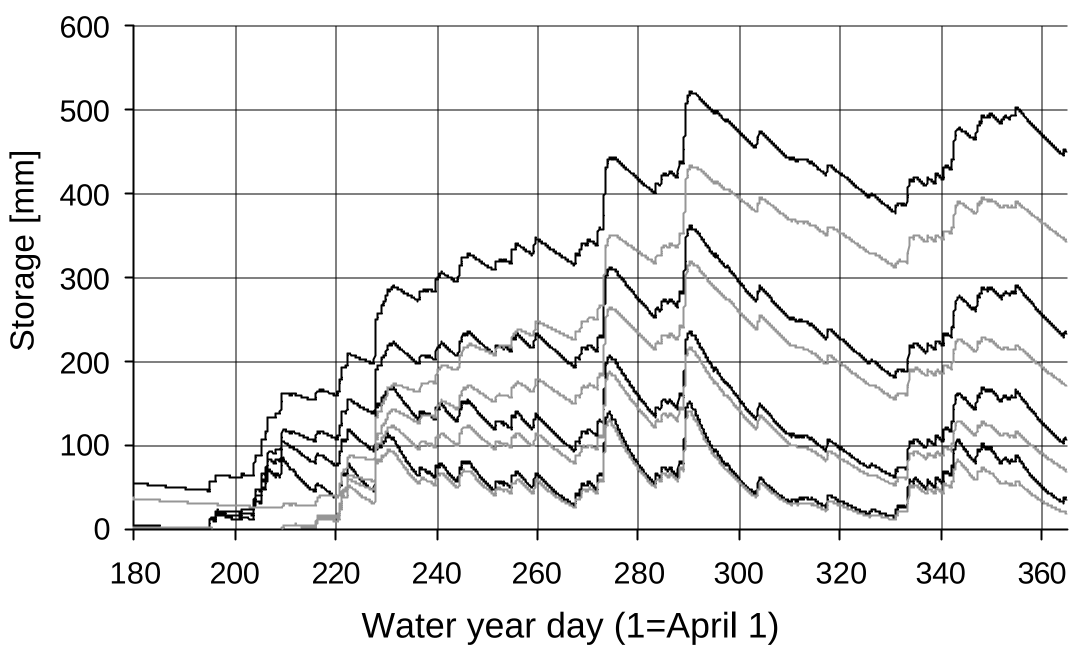

Figure A-3**. Time series of groundwater storage in relation to vegetation cover and t_{90}. Each pair of lines corresponds to a different t_{90}. From uppermost to lowermost pairs, t_{90} is 180, 90, 45, and 21**

days, respectively. The upper (thick black) and lower (thin gray) line of each pair of lines depicts Shrub LOW_ET and Forest HIGH_ET, respectively.

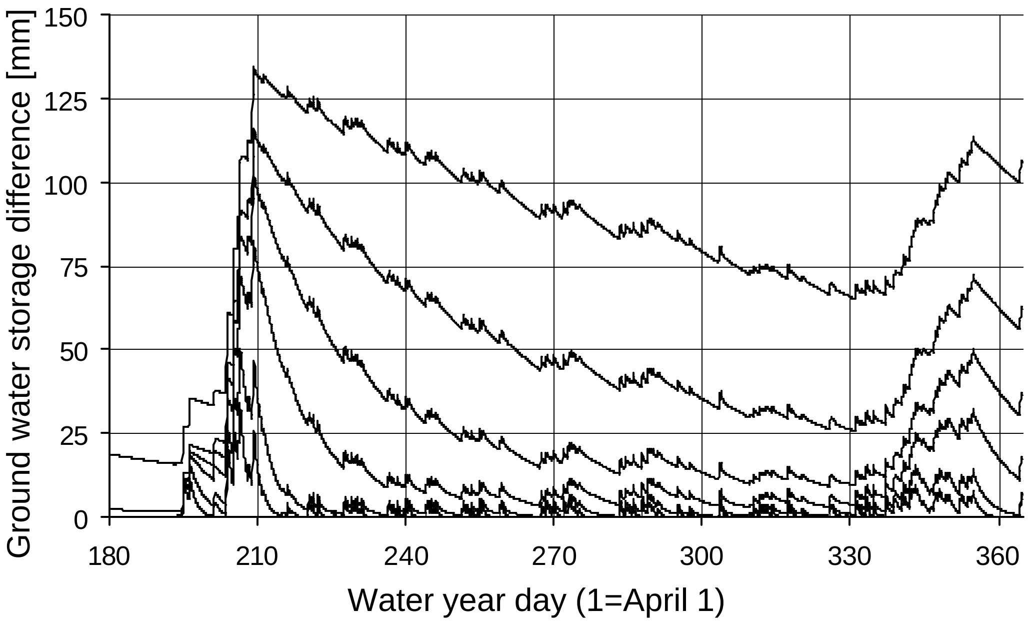

Figure A-4. **Time series of difference in groundwater storage in relation to t_{90} (advection-free simulations): Forest HIGH_ET minus Shrub LOW_ET. From uppermost to lowermost plot, t_{90} is 180, 90, 45, 21, 7, and 3 days, respectively.**

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B Results.

This section is written in the form of a peer-reviewed journal manuscript.

B.1 Abstract.

There is a need for a model which can perform year-round simulations of evapotranspiration and groundwater response for contrasting vegetation types. A model called **GAETP** is described which is tailored to the problem of simulating hydrologic effects of vegetation conversion. This model is an implementation of the Penman-Monteith (**P-M**) equation, the Rutter interception model, and Dupuit-Boussinesq aquifer theory. Moisture content in the vadose zone is represented with a simple bucket model. GAETP has several novel features. 1. The canopy drainage coefficient is determined by canopy interception storage capacity parameter. 2. Rather than treating it as a vegetation parameter, aerodynamic conductance is calculated as the product of vapor drag coefficient and wind speed. Vapor drag coefficient is calculated from momentum drag coefficient by taking into account excess resistance. Finally, momentum drag coefficient is calculated from turbulent diffusion theory for a fully-developed boundary layer, with momentum roughness length and zero-plane displacement indexed to canopy height. 3. The model uses Rossby Similarity Theory for neutrally-stable profiles to adjust windspeed for changes in momentum drag coefficient. 4. Canopy surface conductance is modeled with regression equation for Douglas-fir and salal (Tan et al., 1978). These equations take into account the effects of vapor pressure deficit and soil moisture tension. The first and second features contribute toward a parsimonious parameterization. The third feature is necessary because wind speed has a profound effect on advectively-forced latent heat flux, and is dependent upon surface roughness. For purpose of validation, GAETP was executed with parameters appropriate to evergreen needle-leaf forest, using Surface Airways-derived hourly meteorological data for a location in western Washington, and having a climate characterized by summer drought, and mild, wet winters. GAETP predicts that, in absence of advection, winter evapotranspiration at this site will equal 0.3 times the evaporative equivalent of available radiant energy. This result is discordant with observations of Humphreys (1999) and co-workers (2000, 2002) for a forested site in British Columbia. These researchers found that for each of two full winters of observations, seasonal latent heat flux was equal to available energy, and that half of the latent heat flux occurred at night. An alternative model (**GAETQ**) is described which differs from GAETP only in how it calculates wet canopy evaporation rate in winter: GAETQ uses a fixed potential evaporation rate (**EWP**) in place of the radiation term of the P-M equation. EWP is calibrated so that winter season total latent heat flux equates with net radiation. GAETQ is able to emulate the British Columbia observations. It is argued that, for forest, modeling winter potential evaporation with a calibrated rate constant is more defensible than using the Penman source term (as in GAETP). Uncertainty intervals (UI) for seasonal actual evapotranspiration and groundwater storage were calculated for each of two vegetation covers (forest and shrub). The UI for forest evapotranspiration is small, but the UI for hydrologic effects of vegetation-conversion are large, mainly due to uncertainty as to which version of the model should be applied for shrub.

B.2 Introduction.

Deep-seated landslides are common in the Puget Sound region (Gerstel, et al., 1996; Shipman, 2001), within and outside of populated areas. Occurrences of reactivation or acceleration of motion are strongly correlated with exceptionally wet winters. It is not known, however, whether landslide activity is correlated to vegetation conversion. Koler (1992) shows that there is little empirical evidence on which to make an assesment. Post-dating Koler's (1992) review is a relevant report by Keppeler et al. (1994). They studied changes in pore pressure at the bedrock-soil interface for two winters prior to and for four winters subsequent to harvesting of a forested hillslope. Data from a dense network of monitoring instruments showed that, in compared to an unharvested control watershed, pore pressures were elevated throughout the post-harvest monitoring period.

The present problem requires a better understanding of the difference in forest and non-forest evapotranspiration in all seasons of the year. Unfortunately, most of the empirical and theoretical treatments of forest evapotranspiration to be found in the scientific literature are relevant only to the 'growing season.' Winter interception studies of good quality with respect to instrumentation and sampling density are few in number; the situation is even worse in the case of micrometeorologic experiments. Furthermore, there are almost no multi-season interception and water balance studies that involve a forest and non-forest comparison. There are several excellent review papers on the issue of vegetation conversion effects on evapotranspiration, but again, most of the data reviewed pertains to summer (Jarvis et al., 1976; McNaughton and Jarvis, 1983; Kelliher et al., 1993). Because of this problem, and the obvious problems of large site-to-site variation in important components of the forest and non-forest water budgets, the literature is not at this time especially helpful for multi-season comparisons.

It is this situation that motivated the development of the model described in this paper. The model is tailored to the problem of simulating evapotranspiration for contrasting vegetation types, water table fluctuations, and groundwater discharge for locations where precipitation occurs as rain (rather than as snow or snowmelt). It is applied to answer the following questions: *What is the possible range of decrease in winter and annual evapotranspiration that may result from timber harvest at low altitude in a humid temperate forest? What range of changes in groundwater conditions might result from this decrease in evapotranspiration?*

It is a basic premise of this paper that a careful parameterization and implementation of the Penman-Monteith equation is a valid strategy for gaining theoretical insights into the probable hydrologic effects of vegetation conversion. The model developed for this purpose is described in **Appendix A**. Hourly meteorological data from Seattle-Tacoma International Airport (SeaTac) are used to force the model. The transvaluation procedures described in **§A-4** are designed to address the fact that the vegetation cover at SeaTac is dissimilar to both forest and shrub. The results are divided into two sections. Results I presents the forest validation effort and describes the alternate model. Results II compares the forest and shrub simulation results, and develops the uncertainty intervals. The paper closes with a Discussion section and a Summary and Conclusion section.

B.3 Meteorological data.

B.3.1 Comprehensive hourly data.

The primary source of model forcing data is the **TMY2** product from the National Renewable Energy Laboratory (Marion and Urban, 1995). This data set provides all variables required for applying the P-M combination equation, with the exception of longwave radiation data, at hourly resolution. TMY2 is intended to represent a 'typical meteorological year.' This product has been prepared from National Weather Service data at many airports across the United States, including five locations in the state of Washington (i.e., Spokane, Yakima, Olympia, Seattle-Tacoma, Bellingham, and Quillayute).

The TMY2 consists of a concatenation of month-long sequences of actual hourly meteorological data. For example, at Seattle-Tacoma International Airport (SeaTac), the January record in TMY2 is from the 1988 record, and the February record is an extract from the 1966 calendar year. TMY2 data sets are available for 252 sites in the U.S., and therefore may be a good basis for making inter-regional comparisons of vegetation-conversion effects on subsurface hydrology. Because the input data is limited to 12 months, the model produces only one year of output. This greatly simplifies managing model output files, manipulating the content of model output, calculating statistics, and preparing graphics. The file has no missing data. Use of TMY2 does not permit interannual variability and seasonal-scale and event-scale extremes of weather and climate to be addressed through simulation. The product does not include precipitation, and therefore concurrent hourly precipitation data must be obtained separately from the National Climate Data Center (NCDC).

The TMY2 variables used as direct or indirect forcing data are **1)** extraterrestrial shortwave, horizontal plane ($\mathbf{K_{ex}}$), **2)** incoming global shortwave at surface, horizontal plane ($\mathbf{K_{in}}$), **3)** relative humidity, and **4)** air temperature ($\mathbf{T_{aM}}$), and **5)** wind speed ($\mathbf{U_1}$). Other variables required by the model must be estimated. These include available radiant energy ($\mathbf{Q^*}$), geostrophic windspeed ($\mathbf{V_g}$), wind speed at 2 m above an alternate canopy ($\mathbf{U_2}$), surface and near-surface temperature ($\mathbf{T_s}$, $\mathbf{T_N}$). Of these five estimated variables, only V_g is independent of surface character. U_1 and U_2 will have different values only if the surface roughness parameters assumed in the model run differ from the values assumed under the TMY2 anenometer.

Data from the University of Washington's Wind River Canopy Crane Research Facility (http://depts.washington.edu/wrccrf/) was used to calculate forest albedo and develop regression models for estimating incoming, outgoing, and net longwave radiation. These regression models were needed because longwave data is not provided by the TMY2 data set. **§2-3-2** describes procedures used here to estimate longwave radiation. The Wind River canopy crane is situated in the T.T. Munger Research Natural Area Area in the Gifford Pinchot National Forest. The site is located in the foothills of Mt. Adams, and just to the north of the Columbia River on the Washingon-Oregon border. The T.T. Munger reserve is 400-500 year-old forest dominated by Douglas-fir and Western Hemlock. The tallest trees are 65 m. The crane is situated at the lower fringe of the transient snow zone. The climate is winter-wet summer-dry. Year-to-year variation in winter climate is strong: Snowfall was minimal in winter 1998-1999, but significant snow accumulation occurred in winter 1999-2000. Forest albedo and longwave regressions were estimated using only data from autumn of 1999 and 2000, since the climate in this season resembles the mild winter climate of Puget Sound Lowland. The Wind River data set was evaluated as a source of primary model forcing data, but was found to be inadequate for this purpose, due to extensive data gaps.

B.3.2 Estimation of available energy.

Q* is estimated as the sum of net longwave and net shortwave radiation—i.e., energy storage terms are neglected. Available energy is estimated as

[2-1] $$Q^*_{(t)} = (1-\alpha)K_{in}(t) + L_{net}(t)$$

where

[2-2a] $$L_{net(t|day)} = -10.95[K_{in}^{M}(t)/K_{cc}^{M}(t)]^2 - 85.12\,[K_{in}^{M}(t)/K_{cc}^{M}(t)] + 339.2 - 1.11T_{max(t)} + \delta_{(t)}$$

[2-2b] $$L_{net(t|night)} = 0.15\,\sigma_{sb}\,[T_{a(t)}]^4 - 95\ Wm^{-2} + \delta_{(t)}$$

[2-2c] $$\delta_{(t)} = \sigma_{sb}\,([T_{a(t)}]^4 - [T_{a(t)} + \Delta T_s]^4)$$

, and energy flux density terms have units of have units of Wm^{-2}; net downwelling and upwelling fluxes are assigned positive and negative values, respectively; L_{net} is equal to downwelling minus upwelling longwave radiation (L_{in}-L_{out}); K_{in}^M and K_{cc}^M are mean daytime values of measured downwelling global horizontal shortwave radiation and estimated clear sky insolation, respectively; T_{max} is the daily maximum air temperature [°K]; σ_{sb} is the Steffan-Boltzmann constant; T_a is hourly measured air temperature [°K]; and ΔT_s is the difference between canopy surface temperature and T_a (it is treated as a vegetation-dependent sensitivity parameter). K_{in}^M is calculated from hourly values of K_{in}, which are provided in the TMY2 data set. K_{cc} is estimated from equations given in Bras (1990). According to this model, $L_{net(t|day)}$ is constant during the course of each day-time interval, and energy storage is zero. $\delta_{(t)}$ allows for outgoing longwave to be calculated at canopy surface temperature instead of at air temperature: $\delta_{(t)}$ is zero when ΔT_s (a vegetation parameter) is assigned a value of zero.

The equations for net longwave radiation were developed from the Wind River data. According [2-2b], $L_{net(t|night)}$ is –50.3 and -22 Wm^{-2} at –5 and 30°C, respectively. Measured and modeled energy flux density components and available energy are compared in **Table 2-1** and **Figure 2-1**. The mean absolute error (MEA, Table 2-1) of the modeled flux components is quite good for K_{out} and L_{in}. For Q*, MEA is 25 percent of the mean flux. This large MEA is mainly due to the relatively large MEA for L_{net}.

Table B-1. Comparison of measured and modeled energy flux components at Wind River.[a]

		K_{in}	K_{out}	L_{in}	L_{out}	L_{net}	Q*
Measured		112.7	9.1	327.2	366.5	-39.3	63.6
Modeled		n/a[c]	9.8	327.5[d]	366.8[d]	39.3	63.4
Mean absolute error[b]		n/a[c]	1.47	15.2		15.35	15.5

[a]All fluxes in Wm^{-2}.

[b]K_{in} was not modeled. It is treated as a known input for purpose of estimating Q*.

[c]Model applied and errors calculated at hourly time step. N=3022. [2-2d]

[c]$L_{out}(t)$, modelled = [$L_{net}(t)$, modelled] - σ_{sb} $(T_a(t) + \Delta T_s)^4$

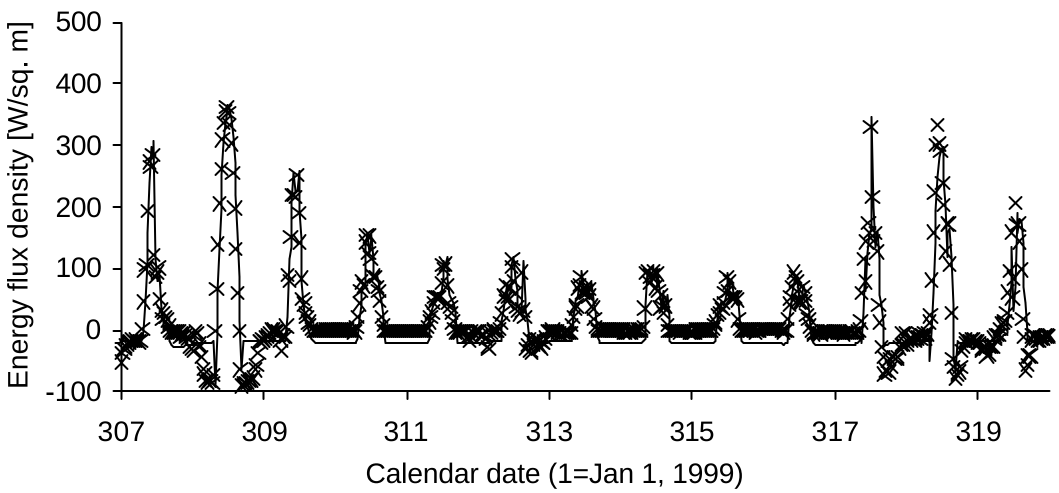

Figure B-1. Sample time series of observed and modeled available energy (Q*) at the Wind River canopy crane: Measured Q* (x) and modeled Q* (line). Observed $Q^*(t) = K_{in}(t) + L_{in}(t) - K_{out}(t) - L_{out}(t)$, where all four terms on the right-hand-side were measured. Modeled $Q^* = (1-\alpha)K_{in}(t) + L_{net}(t)$, where K_{in} is measured, α=0.08, and L_{net} is calculated from [2-2], assuming ΔT_s is zero.

B.4 Parameter bounds.

Parameter sets are established for only two vegetation covers: Forest and shrub (**Table 2-2**). The term 'forest' is used to mean evergeen needle-leaf forest. 'Shrub' is used to mean short evergreen vegetation, and includes sapling conifers, as well as broadleaf shrubs (e.g., salal). Arguably, clearcut would be better modeled as deciduous cover. Except for perhaps the first winter following harvest, shrub is probably more representative of the vegetation cover during at least the first decade following harvest (C. Veldhuissen, pers. commun.).

Parameters are defined so that ‘upper-bound’ value corresponds to high actual evapotranspiration (**AET**) and low recharge, and “lower bound” corresponds to low AET and high recharge. This convention is used to facilitate the determination of uncertainty intervals for model output. The uncertainty interval for each vegetation cover is defined by the two sets of results. These are (a) results obtained with all parameters set to their upper-bound value, and (b) results obtained with all parameters set to their lower-bound value. The greater the extent to which uncertainty intervals for AET and groundwater storage for the two vegetation covers are *non*-overlapping, the more strongly do the model results provide theoretical evidence that actual AET and storage will change significantly after timber harvest.

Table B-2. Upper and lower parameter bounds for forest and shrub.

			PARAMETER VALUES			
			FOREST		SHRUB	
PARAMETER	SEASON[a]	UNITS	HIGH_ET	LOW_ET	HIGH_ET	LOW_ET
$\mathbf{H_c}$ (canopy height)	W,S	[m]	40	40	1	1
D$\mathbf{T_S}$	W	[°C]	0	0	0	0
	S	[°C]	0	0	2[b]	2[b]
a (ALBEDO)	W	[1]	0.08	0.08	0.10	0.20
	S	[1]	0.11	0.11	0.10	0.20
LAI (leaf area index)	W,S	[1]	8	6	4	2
Cx (canopy interception storage capacity)	W,S	[mm]	3.0	1.0	1.0	0.5
$\mathbf{Q_s m}$ (threshold insolation for stomatal opening)	W,S	[W m^{-2}]	50	70	35	70
$\mathbf{r_{st}x}$ (cuticular resistance)	W,S	[s cm^{-1}]	50	100	30	100
RZx (root zone storage capacity)	W,S	[mm]	350	250	250	150

[a]Winter (W) and summer (S).

[b]ΔT_s is 2°C in daytime, and 0°C at night.

Several parameters were set to the same value for all vegetation scenarios, and therefore are not listed in **Table 2-2**. These are temperature threshold for stomatal opening (**Tm**, 2°C); canopy gap fraction (**GF**, 1.0), and infiltration fraction (**INF**, 1.0). Three forest parameters–albedo, leaf area index and canopy height–were set to values from T.T Munger forest (i.e., as estimated from the Wind River canopy crane data) and assigned an uncertainty interval of zero. The Wind River data set showed that L_{out} is well estimated by the Steffan-Boltzman equation, assuming that canopy surface temperature equals air temperature, and surface emissivity is 1.0. This is the reason for choosing ΔT_s is zero for forest. For reason of having lower surface roughness, canopy surface temperature of short vegetation may exceed air temperature. It was decided to set ΔT_s for shrub to 2 °C on summer days, and otherwise to zero.

B.5 Validation.

There are two instrumented tall towers in the Pacific Northwest where multi-seasonal measurements of meteorological variables, latent and sensible heat flux, and gas exchange have been carried out quite recently over Douglas-fir forest. The first of these—Wind River—has already been described **(§2-2-1**). A tower adjacent to the Campbell River, Vancouver Island, British Columbia is situated within a 50 year-old stand. Near to this is a companion tower situated in a clearcut area. These facilities form part of the Ameriflux network (http://public.ornl.gov/ameriflux/). Data from Wind River were used to estimate forest parameters (**§2-3**) and to develop longwave radiation regressions (**§2-2-2**). This data set contained too many gaps—some of weeks in duration—to be useful for validation. Published summaries of observations of seasonal energy, latent heat, and precipitation fluxes at the Campbell River mature-forest tower (Humphreys, 1999; Humphreys et al., 2002) provide opportunity for limited, indirect validation of model predictions for forest cover (**Table 2-3**). No micrometeorological data suitable for validating model predictions over shrub were identified.

The most interesting and relevant results from the Campbell River mature-forest study are (1) interannual variability of winter AET and Q* is minimal, despite large interannual variability of seasonal precipitation total; (2) cumulative AET for each of three winters (**$?_W$AET**) matches the evaporative equivalent of the cumulative net radiation for the same period (**$?_W$Q***); (3) nocturnal AET accounts for half of $?_W$AET, and only 10 percent of summer AET (**$?_S$AET**); (4) during-storm interception loss accounts for 22% of $?_W$AET; (5) transpiration (estimated by dry-canopy latent heat flux) amounts to about 1 inch in winter, and forms a significant portion (30%) of $?_W$AET; (6) interception loss amounts to 5 percent of gross rainfall, and (7) $?_S$AET for each of two seasons of measurements is 318 mm (i.e., for April-September of 1998 and 1999), and is much less than the available radiant energy. Observations (3) and (4), and the fact that the tower is placed so as to minimize horizontal advection, indicate that *vertical* advection is a major mechanism promoting winter AET (see Discussion, **§2-8**).

Table B-3. Results from a multi-season micrometeorological experiment in a Douglas-fir stand on Vancouver Island, Canada (Humphreys, 1999; Humphreys et al., 2001 and 2002).

Interval	Precip.[a]	Net Rad.[a]	Latent heat flux[a]		
			Seasonal	Dry canopy[k]	During-storm[k]
Oct 97-Mar 98[b]	1078	95[i]	101		
Oct 98-Mar 99[b]	1487[g]	101[i]	108		
Oct 99-Mar 00[b]	821[g]	----- (n/r)[h]	119		
Nov 97-Feb 98[c]	----- (n/r)[h]	15[i]	76		
Nov 98-Feb 99[c]	----- (n/r)	16[i]	65		
Winter 98[d,e]	1579	101[j]	114	32	25
Winter 99[d,f]	1640	107[j]	116	36	26
April –Sept. 1998[d]	216	----- (n/r)	318		
April –Sept. 1999[d]	290	----- (n/r)	319		

[a]Precipitation and latent heat flux: Cumulative depth of water in mm (i.e., mm^3/mm^2). Net radiation: evaporative water equivalent of energy flux density in mm depth (cumulative).

[b]Humphreys et al., 2001.

[c]Humphreys (1999), p.82.

[d]Humphreys et al., 2002.

[e]Jan,Feb,Mar,Oct,Nov,Dec of 1998; Humphreys et al., 2001.

[f]Jan,Feb,Mar,Oct,Nov,Dec of 1999; Humphreys et al., 2001.

[g]Snow remained on ground for 3 months. These estimates are likely low due to snow undercatch in 1999 (E. Humphreys, pers. commun.).

[h]n/r = not reported.

[i]E. Humphreys, pers. commun.

[j]Calculated from Table 2 in Humphreys et al., 2002.

[k]Dry canopy: cumulative latent heat flux inclusive of all measurement intervals during which all leaf wetness sensors are dry and/or canopy water balance model indicates canopy is dry. During-storm: cumulative latent heat flux inclusive of all measurement intervals during which gross precipitation observation is non-zero. (E. Humphreys, pers. commun.).

The results of Humphreys (1999) do not appear to be unique to the study site. Several other studies provide empirical evidence that evaporation from a tall forest in a humid climatic region can exceed radiative energy inputs on half-hourly to seasonal and annual bases (Stewart, 1977; Thom and Oliver, 1977; Shuttleworth and Calder, 1970) and at nighttime (Pearce et al., 1980b), even though care is taken to minimize the possibility of horizontal advection. The first three of these four reports described wet season results for United Kingdom coniferous forests. Pearce et al. (1980b) carried out their experiments in a New Zealand broadleaf evergreen forest.

B.6 Application.

There are two TMY2 data sets for two sites in Puget Sound Lowland. These are Olympia Airport and SeaTac. That latter site was selected as the source of forcing data. The TMY2 data for SeaTac is missing the month of December. In order to obtain a full year, the last 15 days of November and the first 16 days of January were used to form a record for December. Concurrent hourly precipitation data was obtained from Earthinfo Hourly Precipitation CDROM. The precipitation data was compared to the TMY2 precipitation flags to verify that the two data sets were consistent.

Total precipitation for the one-year record is 812 mm (32 inches). To bring the precipitation total up to a value that is more representative of the low elevation Cascade foothills along the eastern margin of lowland Puget Sound, winter precipitation (607 mm) was adjusted upward by a factor of 2. With this adjustment, annual precipitation is 56 inches, and 85 percent of precipitation occurs in winter. Relative humidity shows a strong diurnal pattern. Energy flux and unadjusted precipitation is shown on a water year basis in **Figure 2-2**. Interannual variability of root zone soil moisture content is likely to be smaller at end-of-March than at any other time of the year. Therefore, April was selected as the beginning of the water year.

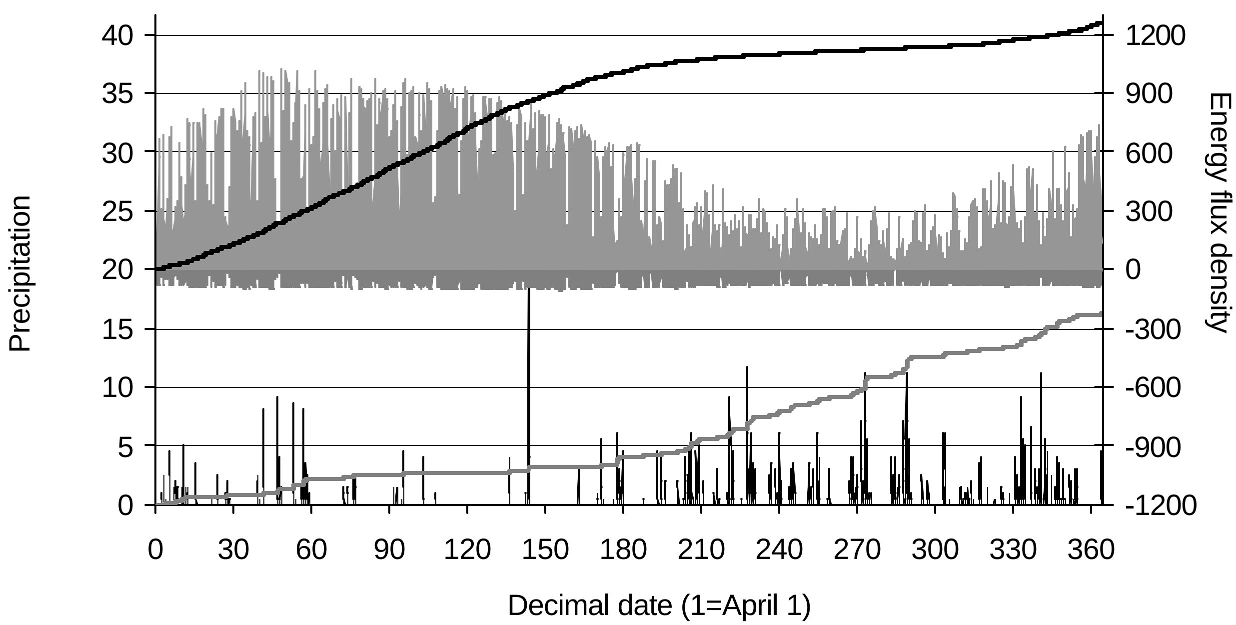

Figure B-2. Time series of hourly radiation and precipitation at SeaTac airport for "Typical Meteorologic Year 2" (TMY2). Decimal date 184.0= midnight, Oct 1. Precipitation is shown without adjustment. The total precipitation for the 12-month sequence is 42 inches.

For this application, the energy balance is calculated for a horizontal surface having no terrain shading. All excess precipitation is routed to the root zone and from there either to the groundwater body or back to the atmosphere as transpiration flux. There is no surface runoff, shallow subsurface stormflow, and macropore flow. Vertical travel time of infiltrate from soil surface to water table is instantaneous. Root zone storage is equal to capacity on day 1 of the water year (April 1). Groundwater storage on April 1 is calibrated for each value of t_{90} so that initial (April 1) and final (March 31) GWS values match.

B.7 Results I: Forest validation.

B.7.1 Validation.

For purpose of comparing model results to Campbell River summary data in **Table 2-3**, the model was run in the advection-free mode, using HIGH_ET forest parameters and SeaTac TMY2 data. The decision to operate in advection-free mode is justified by the fact that the Vancouver Island instrumented tower has been placed so as to minimize horizontal advection. GAET appears to give valid results for dry season: The simulated summer AET at SeaTac is 303 mm—very close to the measured dry season AET at the Vancouver Island study site. In several important respects, the model results agree poorly with the Vancouver Island observations. GAET predicts that 1) the ratio [?AET/ ?Q*] in winter at SeaTac, in advection-free circumstances, is 0.3 (**Table 2-4**); 2) nocturnal latent heat flux is zero throughout the year; 3) winter interception loss is only 2 percent of gross precipitation; and 4) winter transpiration accounts for 65 percent of winter AET.

Table B-4. Simulation statistics for advection-free runs with forest parameters: Original model (GAETP).

Interval	Pg[a] [mm]	Q* [mm]	E_{eq}[b] [mm]	AET [mm]	AET/Q* [1]	α_{PT}[c] [1]	TR [mm]	IL/ Pg [1]	AET fraction TR	night	during-storm
APR-SEP	205	1023	676	303	0.30	0.45	277	0.13	0.91	0.0	0.02
OCT-MAR	1214	253	140	74	0.29	0.53	48	0.02	0.65	0.0	0.08
ANNUAL	1419	1275	816	377	0.30	0.46	324	0.04	0.86	0.0	0.02

[a]Pg: gross precipitation; TR: transpiration. IL: interception-loss.
[b]E_{eq} is the radiation term of Penman potential evaporation.
[c]α_{PT} is the Preistley-Taylor coefficient. It is equal to AET/ E_{eq}.

In order to better emulate the Vancouver Island observations, GAET was modified so that winter AET matches the available radiant energy. The original and modified models will be denoted **GAETP** and **GAETQ**, respectively. GAETP and GAETQ differ only in how they calculate potential evaporation rate ($PEV_{(t)}$) in winter.

GAETP (all seasons); GAETQ (summer): $PEV_{(t)} = \alpha_{eq}(t)Q^*(t) + f(u(t))$

GAETQ (winter): $PEV_{(t)} = EWP + f(u(t))$

$\alpha_{eq}Q^*$ and $f(u)$ represent the source and sink terms, respectively, of the Penman combination equation. a $_{\mathbf{eq}}$ is the radiation partitioning coefficient (i.e., $\alpha_{eq}=\Delta/(\Delta+\gamma)$). It is a function of near-surface air temperature, and falls within the range 0.4 to 0.7 in the temperatures that prevail in western Washington. At SeaTac, the winter mean value of α_{eq} is 0.55, and the summer mean is 0.65 (these values were calculated from the TMY2 data). **EWP** is time-invariant, and is calibrated so that $?_W$AET in advection-free runs equals $?_W$Q*. Both versions of the model use the P-M equation to calculate dry-canopy transpiration throughout the year.

It was found that two values of EWP were needed in winter in order to obtain a reasonably good calibration (**Table 2-5**). EWP was set to 0.4 mm hr^{-1} for October and March, and to 0.1 mm hr^{-1} for November through February. **Table 2-6** compares results from both versions of the model to observations at the Vancouver Island canopy crane. This comparison is sensible if two assumptions are justified: 1) The Vancouver Island observations are not atypical of forests in a mild wet winter/ dry summer climate, and 2) these metrics are insensitive to site-differences in climate. These assumptions are discussed in §2-9.

Table 2-6 shows that for the three quantities—[$?_W$AET/$?_W$Q*], fraction of $?_W$AET and $?_S$AET that occurs at night, and $?_S$AET—the GAETQ results compare well with the observations. GAETQ overpredicts the fraction of $?_W$AET that is due to during-storm evaporation; nevertheless, with respect to this metric, GAETQ performs better than GAETP. Neither version of the model produces an interception loss rate that matches the observed value. Still, the 16% interception loss rate obtained with GAETQ is quite reasonable for a closed canopy needle-leaf forest (Patric, 1966). The two models give similar absolute values for winter transpiration total (i.e., nearly 50 mm); this result compares reasonably well to the observed winter dry-canopy latent heat flux (34 mm). Winter transpiration is similar for the two versions of the model because both versions use the P-M equation to calculate potential transpiration.

Table B-5. Simulation statistics for <u>advection-free</u> runs for forest: Modified model (GAETQ)

Interval	Pg[a] [mm]	Q* [mm]	E_{eq} [mm]	AET [mm]	AET/Q* [1]	α_{PT} [1]	TR [mm]	IL/ Pg [1]	AET fraction TR	AET fraction night	AET fraction during-storm
APR-SEP	205	1023	676	275	0.27	0.41	249	0.13	0.90	0.0	0.02
OCT-MAR	1214	253	140	246	0.97	1.75	46	0.16	0.19	0.41	0.41
OCT	166	61	37	58	0.95	1.55	13	0.27	0.23	0.31	0.40
NOV-FEB	825	101	52	96	0.95	1.84	15	0.10	0.16	0.48	0.36
MAR	223	91	51	92	1.01	1.82	18	0.33	0.19	0.39	0.45
Annual	1419	1275	816	521	0.41	0.64	295	0.16	0.59	0.19	0.20

[a]See footnotes to **Table 2-4**.

Table B-6. Comparison of Vancouver Island observations[a] to model results for a forest stand at SeaTac.

Metric[b]	Observed	Modeled GAETP	Modeled GAETQ
1. $?_W$AET/ $?_W$Q*	1.0	0.29	0.97
2. Nocturnal fraction of $?_W$AET	0.5	0.0	0.41
3. Nocturnal fraction of $?_S$AET	0.1	0.0	0.0
4. During-storm IL as fraction of $?_W$AET	0.22	0.08	0.41
5. Transpiration, winter total	34	48	46
6. Interception loss ratio, winter[c]	0.05	0.02	0.16
7. Evapotranspiration, summer total (i.e., $?_S$AET)	318	303	275

[a]50-year old Douglas fir stand (see **§2-4**).

[b]All values are ratios, except for $?_S$AET and transpiration, which are given in mm. $?_W$AET, $?_W$AET , and $?_W$Q* where defined in **§2-4**.

[c]Interception loss divided by gross precipitation.

B.7.2 Contribution of horizontal advection to seasonal latent heat flux.

Table 2-7 gives results from two simulations in which the parameter sets are identical except for canopy height. Surface roughness is an important determinant of the magnitude of the horiziontal advection term; in GAET (both versions), surface roughness is a function of canopy height. The second set of results uses 1.0 m for canopy height, as this is the assumed value for shrub. For each canopy height, results are given for an advection-free run, and a run using measured relative humidity (i.e., that labelled 'strong advection'). Q* is 253 mm. In the advection-free GAETQ simulation ?$_w$AET is approximately equal to ?$_w$Q*, not by coincidence, but because EWP was calibrated to achieve this result.

Table B-7. Forest HIGH_ET simulation results.

	40 m-tall forest [a]						1.0 m-tall forest [b]					
	No advection			Strong advection[c]			No advection			Strong advection[c]		
Season	AET	IL	TR	AET	IL	TR	AET	IL	TR	AET	IL	TR
OCT-MAR	246	200	46	1074	597	478	254	200	55	1019	518	502
APR-SEP	275	26	249	550	106	445	311	26	284	551	93	458
Annual	521	226	295	1625	702	923	565	226	339	1570	610	960

[a] Forest HIGH_ET parameter set.
[b] Forest HIGH_ET parameter set, except that canopy height is set to 1.0 m.
[c] Using TMY2 relative humidity data without adjustment.

In the advection-free simulation, winter AET for 40 m-tall forest is 246 mm. Strong-advection causes winter AET to increase by 300 percent to 1074 mm. Increased transpiration accounts for fully half (52 percent) of the 828 mm increase in winter AET. Transpiration is only 20 percent of winter AET in the advection-free case, but is 45 percent of winter AET in the strong-advection case. The results for the 1.0 m canopy are similar.

Table 2-7 illustrates several important results. Firstly, the advection-forcing of latent heat flux can be much larger than the radiative-forcing. Secondly, a large contrast in surface roughness has little effect on the magnitude of the advection term. Thirdly, the proportional increase in AET induced by advection is smaller in summer than in winter. This is due to a moisture-supply limitation in summer.

The large transpiration loss in winter in the strong-advection case seems quite unrealistic. This result brings into focus two major weaknesses in model. Firstly, due to poor information about the magnitude of and the factors controlling winter transpiration in evergreen vegetation, the algorithms for summer were applied to winter. The only provision made to limit winter transpiration flux was to restrict transpiration to days when night minimum air temperature exceeds 2 °C. It seems likely that high soil water viscosity would have considerable influence on winter transpiration flux, and that had this been taken into account, the simulated winter transpiration fluxes would be much smaller.

Secondly, the dependence of relative humidity (**RH**) on surface latent heat flux was not taken into account. The TMY2 relative humidity data is representative of an extensively poorly-vegetated surface. One would expect relative humidity to increase downwind of a transition from a poorly-vegetated to a well-vegetated tract. It seems justified to treat RH as a sensitivity variable. **Table 2-8** shows the seasonal latent heat fluxes obtained with the following RH scenario: In summer, TMY2 data is used, i.e., without adjustment for vegetation cover. In winter, during-storm RH is set to 1.00, and between-storm RH is set to 0.95. The terms during-storm and between-storm simply mean rainy- and rain-free hours, respectively. This will be referred to as the 'moderate-advection' scenario. Just as happens in the strong advection scenario, surface roughness has little influence on the results. Notice that summer AET is similar in the strong-advection and moderate advection simulations, but that winter AET in the moderate-advection scenario is intermediate with respect to the advection-free and strong-advection scenarios.

Table B-8. Forest HIGH_ET simulation results, moderate-advection scenario[a].

	40m-tall forest forest[b]					1.0 m-tall forest[c]				
Interval	AET[d] [mm]	IL [mm]	TR [mm]	AET/Q_W [1]	AET/Pg [1]	AET [mm]	IL [mm]	TR [mm]	AET/Q_W [1]	AET/Pg [1]
OCT-MAR	441	295	146	1.75	0.36	410	271	139	1.62	0.34
APR-SEP	550	106	445	0.54	2.68	551	93	458	0.54	2.69
Annual	992	401	590	0.78	0.70	961	364	597	0.75	0.68

[a]RH is set to 1.00 during rainy winter hours, 0.95 during non-rainy winter hours, and measured value during all summer hours.
[b]Forest HIGH_ET parameter set [Runs FHAh, FHAi].
[c]Forest HIGH_ET parameter set, except that canopy height is set to 1.0 m [Runs FHAg, FHAf].
[d]IL: interception loss; TR: transpiration; P_g: gross precipitation.

Summer AET increases from 275 mm in the advection-free run to 550 mm in the moderate advection scenario. Summer AET does not increase further in the strong-advection scenario. The summer-value of the radiation partitioning coefficient is 0.65. This, and two other factors—limited moisture supply and canopy surface resistance to transpiration—explain why AET is only about 25 percent of the available energy (1023 mm). The moisture supply in summer is equal to root zone storage capacity (350 mm for forest HIGH_ET) plus April-September cumulative precipitation (205 mm). The sum of these—550 mm—matches the summer AET in the moderate and strong advection scenarios. It appears that, without advection, summer AET will be less than the supply; on the other hand, only weak advection is required to obtain summer AET that matches the moisture supply.

It is unlikely advection is zero in summer, because of the droughty climate. Therefore, it is safe to assume that summer AET equates with the sum of RZX plus summer precipitation plus capillary upflux. According to this model, and apart from possible differences in capillary upflux, vegetation-related differences in summer latent heat flux will be less than or equal to the difference in root zone storage capacity.

Seasonal and annual latent heat flux totals in the advection-positive runs is very similar for 40.0 m and 1.0 m canopies. This results shows that, according to the model, large differences in surface roughness do not produce large differences in latent heat flux.

B.7.3 Considerations for application to shrub.

Table 2-9 shows advection-free simulation results for shrub, with all parameters set to their LOW-ET bound. Summer AET is similar for both model versions, with and without advection, as it should be. When potential evaporation is calculated with the Penman equation, only 20 percent of Q* is converted to latent heat flux in winter, and nocturnal flux is zero throughout the year. There is a strong contrast in seasonal and annual AET for the two model versions: The winter, summer, and annual AET ratios for the two models (i.e., GAETP versus GAETQ) are 0.20, 0.96, and 0.52.

Table B-9. Shrub LOW_ET simulation results[a].

	GAETP (using Penman source-term)			GAETQ (EWP used in place of Penman source-term)		
Interval	AET[b]	IL	TR	AET	IL	TR
			----- advection-free -----			
OCT-MAR	41	19	22	208	183	25
APR-SEP	147	21	126	153	21	132
Annual	188	40	148	361	204	157
			----- moderate-advection -----			
OCT-MAR	144	86	57	272	214	58
APR-SEP	334	92	242	334	92	242
Annual	487	179	299	606	306	300

[a]Q* is 202 and 899 mm in winter and summer, respectivey. E_{eq} in winter is 110 mm.
[b]AET: actual evapotranspiration; IL: interception loss; TR: transpiration.

It is not known whether EWP should be used in the case of shrub. There is ample evidence that AET of “well-watered” crops and wet forest (both broadleaf and needle-leaf) in the growing season obtains Q*. There is no physical rationale for supposing that this balance of AET and Q* does not also obtain in the case of short green vegetation in a mild wet winter climate. It was decided to use the Penman equation to simulate potential evaporation for the LOW_ET case, and to use EWP for the HIGH_ET case. Winter interception loss is quite sensitive to whether EWP or the Penman source term is used to simulate the radiation-forced potential evaporation (**Table 2-9**). The difference in results between the GAETP and GAETQ is smaller when advection is permitted.

EWP changes when Q* changes. Shrub HIGH_ET has albedo and Q* similar to the forest (i.e., 0.1 and 244 mm, respectively). Therefore, EWP was set to the same calibrated value as used for forest. Shrub HIGH_ET simulation results are shown in **Table 2-10**.

Table B-10. Shrub HIGH_ET simulation results.

	Advection-free			Moderate advection		
	AET	IL	TR	AET	IL	TR
OCT-MAR	242	195	47	366	243	124
APR-SEP	251	26	255	450	95	355
Annual	492	221	272	816	338	479

B.8 Results II. Vegetation conversion effects.

All results are given as time series, with day numbers referenced to the water year. **Table 2-11** shows the the correspondence of water year days to calendar months.

Table B-11. Water year day number corresponding to first day of calendar month.

Month	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	March
Day #	1	32	63	93	124	155	185	216	245	276	307	335

Note that root zone discharge is exactly equivalent to groundwater recharge (**GWR**), since the model assumes instantaneous translation of outflow from the base of the root zone to the water table. Also, keep in mind that the groundwater simulation results only reflect *local* contributions to groundwater storage (**GWS**), but not intermediate and regional-scale contributions. So for these simulations, it is helpful to think of the model as representing a closed basin with an aquifer that receives only local recharge. It must also be kept in mind that *storage* must be divided by effective porosity (n_e) to obtain piezometric head (height of water table above bedrock). Porosity is necessarily less than unity and greater than zero for all porous media. If porosity is 0.1, then water table thickness will be 10 times larger than storage. For the Dupuit-Boussinesq aquifer, storage divided by n_e represents average water table thickness along the water table profile, i.e., from seepage face to divide.

GWS is determined by the joint time series of inflows (i.e., recharge) and outflows (i.e., discharge). Outflow is determined by storage level, and by the effective hydraulic conductivity of the aquifer. It is convenient to express effective aquifer hydraulic conductivity in terms of t_{90}. t_{90} is mathematically-related to aquifer breadth and hydraulic conductivity. t_{90} is the time required for groundwater storage to drop by 90 percent, or to 10 percent of its initial value, during a period of no-recharge. t_{90} increases with aquifer breadth for a given hydraulic conductivity. For a given aquifer breadth, t_{90}=7 days represents a more conductive, rapidly responding reservior, say, a sand box; t_{90}=180 days could represent a highly retentive, slowly responding clay deposit.

B.8.1 Seasonal latent heat flux contrast for forest and shrub.

Figure 2-3 shows the transpiration and evaporation components of the seasonal and annual water balance for advection-free simulations. The uncertainty interval for the forest seasonal and annual water balances are small. With the high-ET parameter set, annual AET is 521 mm. Annual AET differs by only about 6 percent (31 mm) between the HIGH_ET and LOW_ET runs, and this difference is mainly due to the difference in summer transpiration (21 mm). Sensitivity analysis showed that albedo is the only parameter which strongly influences interception loss (**IL**). The uncertainty interval for albedo was set to zero; this explains why the winter and summer IL is very similar for the two runs. RZx is the only parameter that has a non-zero uncertainty interval *and* strongly influences transpiration (**TR**). It this parameter that accounts for the 21 mm difference in summer TR.

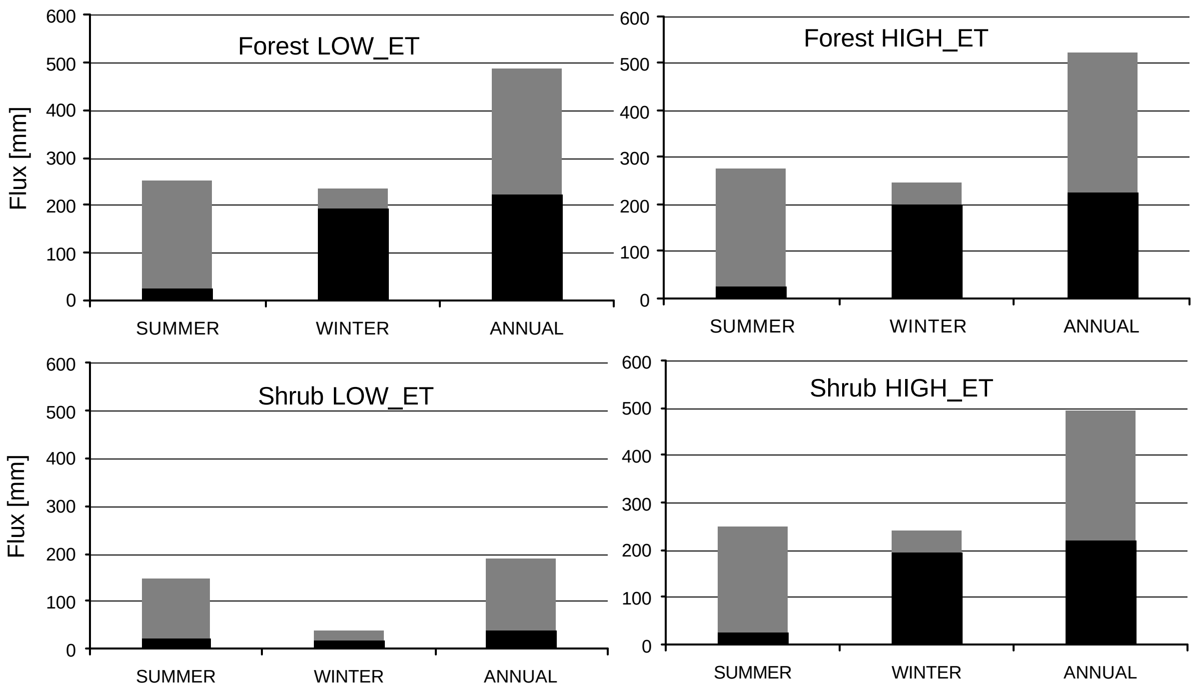

Figure B-3. Seasonal and annual water balance for advection-free simulations: Interception loss (black) and transpiration (gray).

The uncertainty interval for the shrub water balance is large. Annual AET is 188 and 492 mm for the LOW_ET and HIGH_ET runs, respectively. This difference of 304 mm is due mainly to decreased winter IL (-176 mm) and decreased summer TR (-99 mm). Summer IL changes little between the two runs. Sensitivity analysis was performed to identify influential parameters. The much smaller winter IL obtained in the LOW_ET run is due to higher albedo and the use of GAETP (i.e., P-M equation) for winter potential evaporation. The difference in summer transpiration was traced to a single parameter—r_sx. Although there are several parameters whose effects are limited to transpiration, (LAI, Q_sm, r_sx), r_sx explains nearly 100 percent of the uncertaingy in summer AET and one-third of the uncertainty in annual AET in the shrub simulations.

B.8.2 Soil moisture patterns.

Figure 2-4 shows the time series of root zone storage for advection-free simulations. In each case, the start- and end-of-water year storage is equal to RZx (see **Table 2-1**). The pattern of soil moisture content is related to the balance between precipitation and atmospheric evaporative demand. Beginning early July and continuing through mid-August (August 15 is water year day 138)), rainfall is less than evapotranspiration demand, causing root zone to storage to decline fairly steadily. Root zone storage is fairly stable for the next month, and then begins to climb in mid-September. Beginning mid-September, the moisture supply exceeds the atmospheric demand.

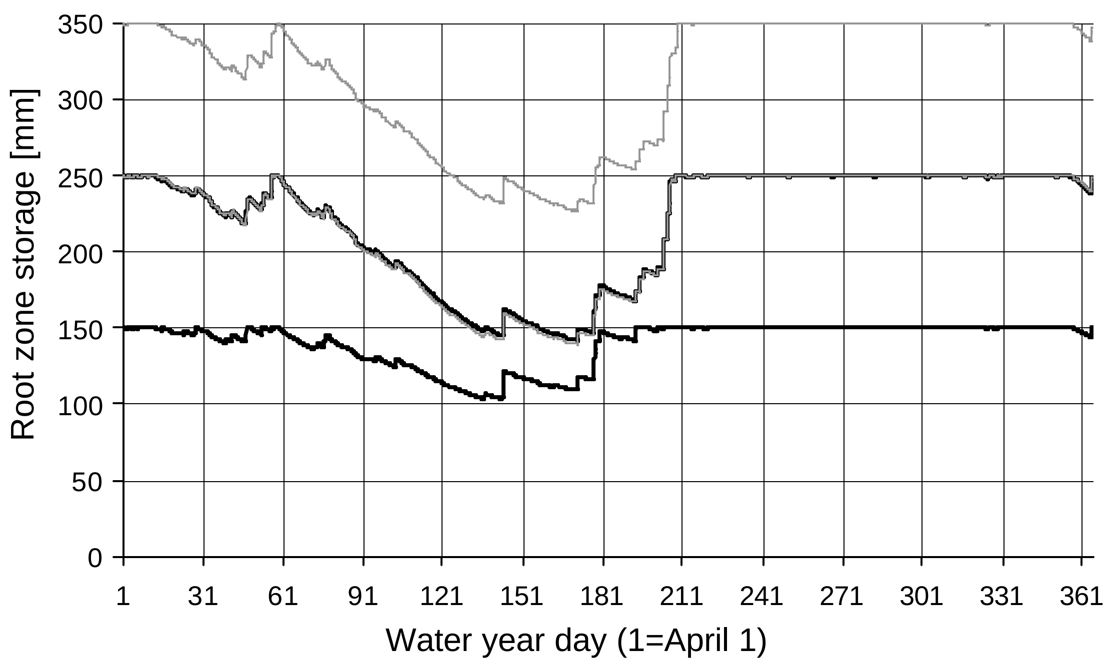

Figure B-4. Time series of root zone storage (advection-free simulations). Forest HIGH_ET (upper plot); Forest LOW_ET (middle plot); Shrub HIGH_ET (middle plot); Shrub LOW_ET (lower plot). Forest LOW_ET and Shrub HIGH_ET plots are not differentiable on this graph because they are nearly identical.

The first several storms in autumn cause root zone storage to increase rapidly. As soon as storage reaches its maximum value (RZx), the root zone is fully-rehydrated, and seasonal groundwater recharge begins. The timing of onset of seasonal groundwater recharge is earliest for the shrub LOW_ET scenario (day 190), and latest for the forest HIGH_ET scenario (day 210); for shrub HIGH_ET and forest LOW_ET, onset of recharge occurs just a couple days early than for forest HIGH_ET.

The time series of groundwater storage are quite similar for three of the four simulations (**Figure 2-5)**. The Forest HIGH_ET, Forest LOW_ET, and Shrub High_ET groundwater storage time series are similar regardless of choice of t_{90}, and regardless of whether advection is allowed. The only non-trivial comparision is between Shrub LOW_ET and Forest HIGH_ET. This comparison stands as the upper end of the uncertainty interval for the effect of vegetation conversion on groundwater recharge.

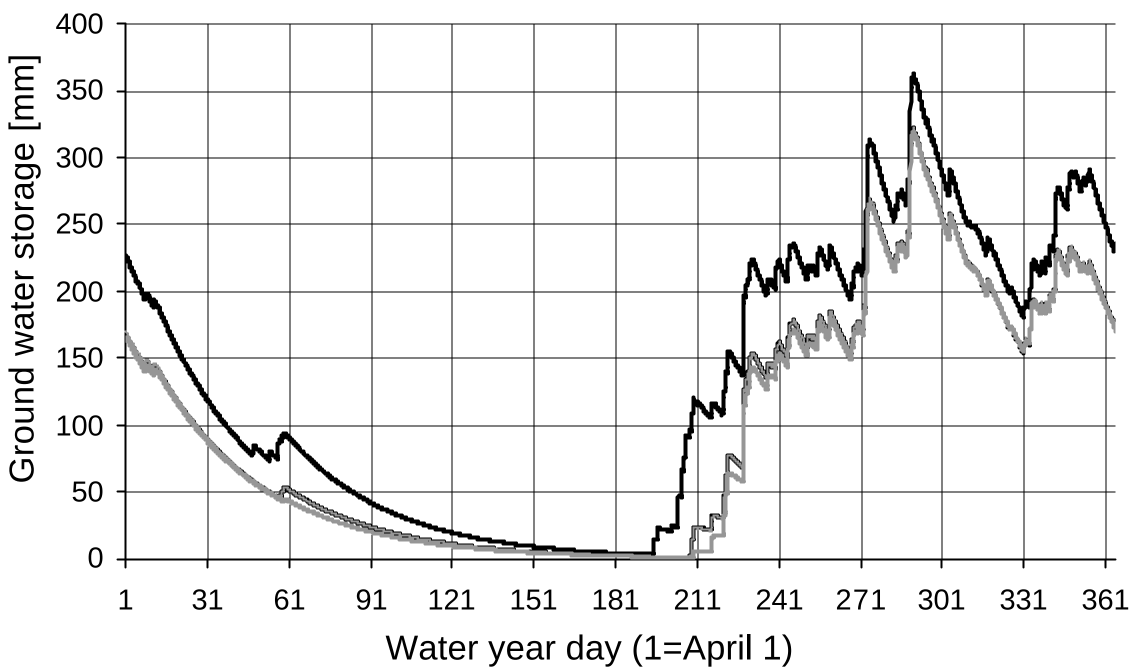

Figure B-5. Time series of groundwater storage for t_{90}=90 days (advection-free simulations). Shrub LOW_ET (upper plot); Shrub HIGH_ET (middle plot, black line); Forest LOW_ET (middle plot, gray line); Forest HIGH_ET (lower plot). Forest LOW_ET and Shrub HIGH_ET plots are nearly identical.

Figures 2-6 and 2-7 show the effect of t_{90} on groundwater storage (GWS), and GWS *difference* ($\Delta S_{(S-F)}$), respectively, for the Shrub LOW_ET and Forest HIGH_ET cases. At low t_{90} (3-days is the smallest value for which results are shown) there is almost no vegetation effect except for the first two months and the last three weeks of the wet season. At high t_{90} (results for t_{90}=180 days are shown), a vegetation effect persists throughout the wet season. t_{90} affects the magnitude, but not the timing, of the seasonal peak GWS. The largest values of $\Delta S_{(S-F)}$ occur early in the wet season (**Figure 2-7**). This is attributable to the delayed timing of full-rehydration of the root zone in the forest simulation; this, in turn, is caused by RZx (i.e., root zone storage capacity) being larger for forest. t_{90} has a strong influence on magnitude of the initial forest-shrub difference in water table elevation, and the rate at which difference dissipates as the wet season progresses.

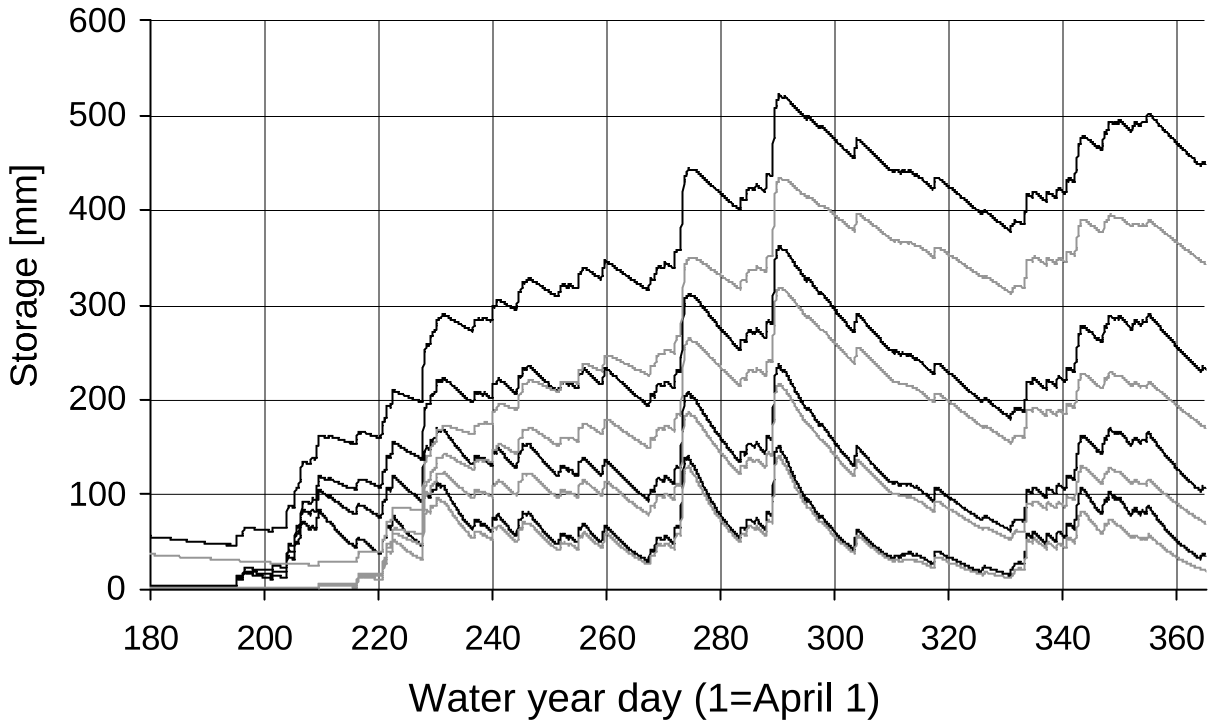

Figure B-6. Time series of groundwater storage in relation to vegetation cover and t_{90}. The upper (thick black) and lower (thin gray) line of each pair of plots depicts Shrub LOW_ET and Forest HIGH_ET, respectively. Each pair of lines correspondes to a different t_{90}. From uppermost to lowermost pairs, t_{90} is 180, 90, 45, and 21 days, respectively.

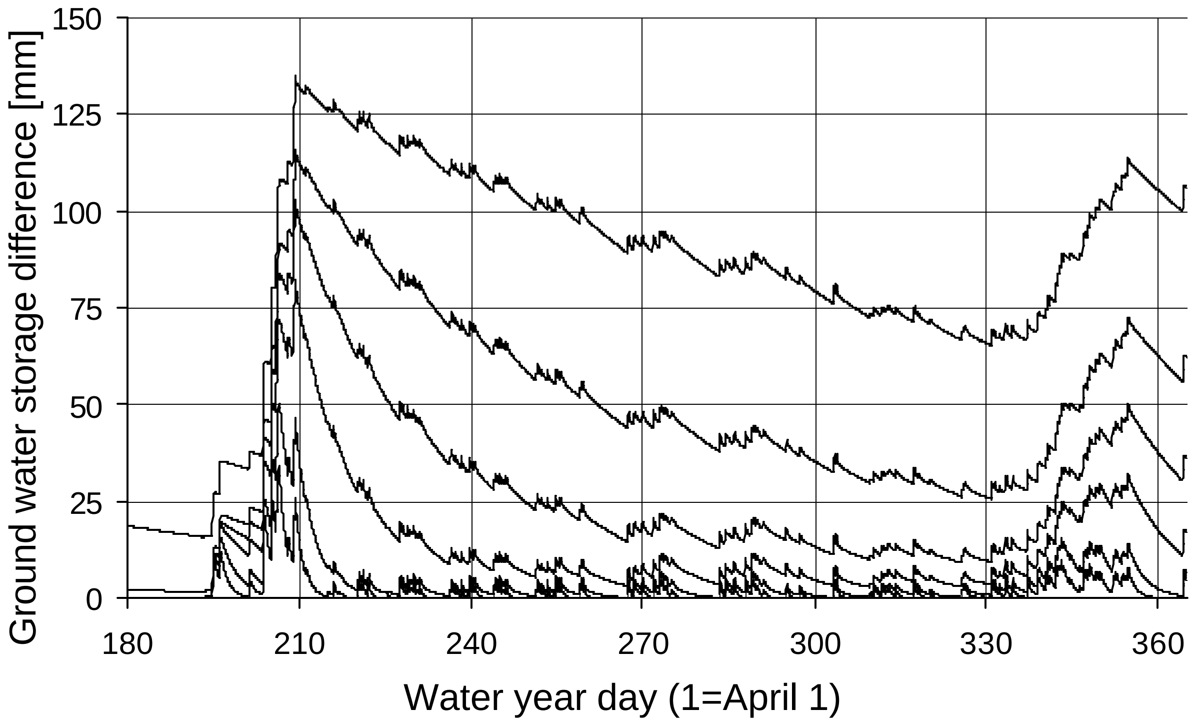

Figure B-7. Time series of difference in groundwater storage in relation to t_{90} (advection-free simulations): Forest HIGH_ET minus Shrub LOW_ET. From uppermost to lowermost plot, t_{90} is 180, 90, 45, 21, 7, and 3 days, respectively.

For t_{90}=7 days and less, $\Delta S_{(S\text{-}F)}$ never exceeds 10 mm after day 220. For t_{90}=21 days and 7 days, $\Delta S_{(S\text{-}F)}$ remains above 20 mm for nearly three weeks and three days, respectively. For t_{90}=180 days, $\Delta S_{(S\text{-}F)}$ is never less than 70 mm throughout the wet season. If n_e were 0.1, then, for t_{90}=180 days, the profile-mean water table elevation is predicted to be at least 0.3 m higher for shrub throughout the wet season, and to exceed 0.8 m from late October through late November.

When advection is allowed to occur, GWS decrease for both scenarios, but the decrease in forest GWS is larger. Consequently, then the vegetation-related difference in GWS becomes larger (Figure 11). Moderate advection causes full replenenishment of root zone moisture content to be delayed by about one month and two months, respectively, for shrub and forest. Winter AET fluxes increase by about the same amountn for both vegetation covers.

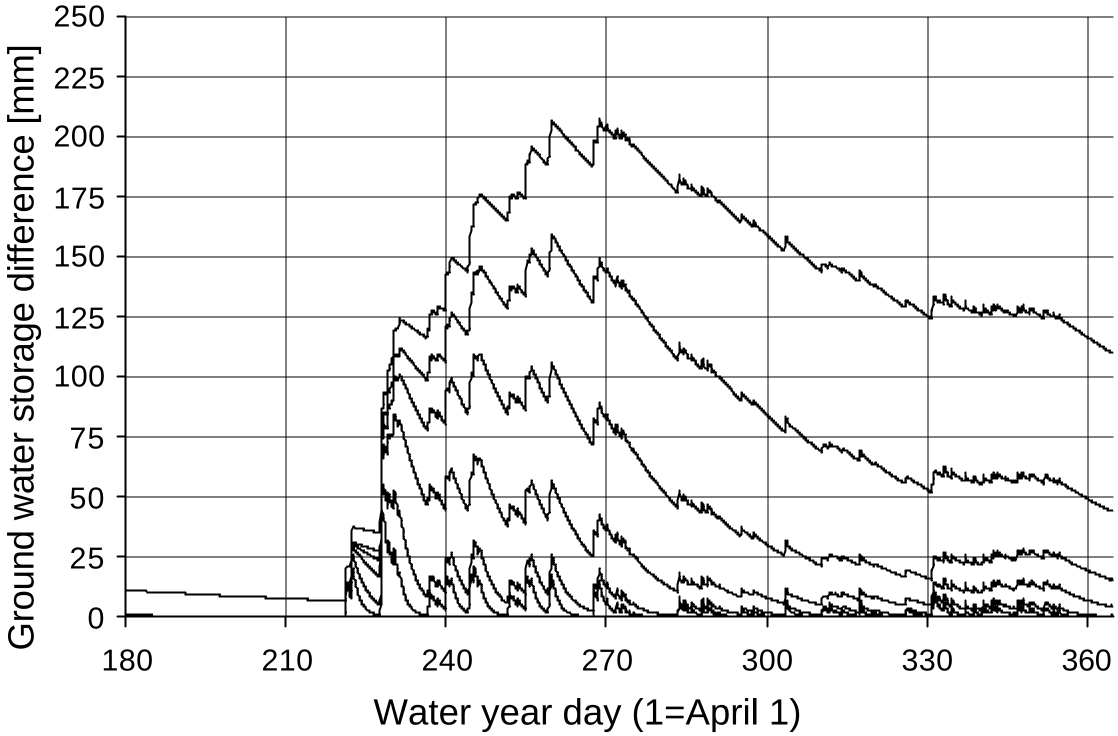

Figure B-8. Difference in in locally-produced groundwater storage in relation to t_{90}., moderate-advection scenario. From uppermost to lowermost plot t_{90} is 180, 90, 45, 21, 7, and 3 days. Ecah plot gives storage for Shrub LOW_ET minus storage for Forest HIGH_ET.

B.9 Discussion

Simulation results for the strong-advection cases predict that—regardless of canopy height—all or nearly all of winter precipitation can be returned to the atmosphere as evapotranspiration. This extremely unrealistic result is due to the fact that (1) the model does not address the negative feedback of latent heat flux onto relative humidity, and (2) the surface at SeaTac is poorly vegetated. Relative humidity as measured at SeaTac is much lower in winter than what would be observed if an extensive vegetation cover were present.

Three considerations justify the decision to ignore horizontal advection in winter:

1) Horizontal advection is likely to be significant only for short distances downwind of transitions in landscape surface properties (McNaughton and Jarvis, 1983).

2) Horizontal advection would tend to *suppress* evaporation over short wet vegetation when the upwind terrain is wet forest; conversely, horizontal advection would tend to *enhance* evaporation

over wet forest when the upwind terrain is wet short vegetation (McNaughton and Jarvis, 1983). (Note that the first of these two situations is most relevant to harvest.)

3) Because the atmospheric boundary layer (**ABL**) is frequently stable in winter, horizontal-advective enhancement and suppression of latent heat flux is likely to be weak.

Groundwater storage is sensitive to winter evaporation, and largely insensitive to summer AET (except insofar as summer AET affects timing of the start of the groundwater recharge season). Therefore, it is important to take a critical look at the justification for and weaknesses of GAETQ, and at the justification for the decision to use GAETP for the Shrub LOW_ET simulation and GAETQ for the other three vegetation scenarios.

If radiation is the only source of energy for evaporation, then the expected latent heat flux occurs at the equilibrium rate ($\alpha_{eq}Q^*$), which—at low, above-freezing air temperature—is about 40 percent of the evaporative equivalent of net radiation. At the Vancouver Island study site, October-March equilibrium evaporation is about 40 mm. The measured winter (Oct-Mar) evaporation (100 mm) exceeds equilibrium evaporation by about 60 mm. Given that the B.C. tower was placed so as to minimize horizontal advection, we assume that the excess evaporation is due to vertical advection. This mechanism has been eloquently described by De Bruin and Jacobs (1989) and will not be reviewed here. Its occurrence is limited to stable ABLs during rainfall and subsequent drying of a wet canopy. It does not require an input of radiant energy, and can induce latent heat flux even at night when the surface energy balance is negative. It is associated with a small near-surface vapor pressure deficit (vpd), but this non-zero vpd is an integral feature of the mechanism—it is not the *cause* of vertical advection (De Bruin and Jacobs, 1989). At middle and high latitudes in winter, rainfall is usually associated with a stable ABL. Mizutani et al. (1997) showed that the P-M equation is able to correctly simulate the actual latent heat fluxes from a wet canopy during vertical advection events, provided that good information on the surface windspeed and vapor pressure deficit is available.

GAETQ is, in effect, a simple-minded way to allow for vertical advection. McNaughton and Jarvis (1983) suggest that high surface roughness is required to enable vertical advection to occur. The author is not aware, however, of any empirical experiments having been undertaken to determine whether vertical advection is a common or rare occurrence over wet *deforested* patches. In the author's opinion, there is not sufficient theoretical understanding nor empirical information to justify a decision to use one version of the model in favor of the other in the case of non-forest vegetation, and therefore model structure must be admitted to be a major source of uncertainty in the shrub simulations.

To make an objective assessment of the contribution of vertical advection to $?_W$AET would require the use of a detailed multi-layer model of the ABL and knowledge of the potential temperature and humidity profiles just above the top of the ABL (i.e., at the bottom of the overlying free atmosphere; De Bruin and Jacobs, 1989). To take this route was not feasible; therefore, to implement GAETQ, it was necessary to make what is in fact an arbitrary decision about what value the parameter EWP should take. The decision to calibrate EWP so that $?_W$AET matches $?_W Q^*$ is based only on Humphreys et al.'s (2001) observations at their Douglas-fir study site that a) [$?_W$AET/ $?_W Q^*$~1] for each of three consecutive winters, and b) $?_W Q^*$ was similar for each of the three winters. Considering that the observed interannual variability of winter precipitation was large, these observations are particularly impressive; nevertheless, the possibility that these results are merely coincidental cannot be ruled out.

Uncertainty about how EWP should be calibrated means that the absolute values of winter latent heat flux over forest as predicted at SeaTac should not be interpreted too literally. Still, lack of knowledge about which version of the model to use for shrub is much more significant than lack of knowledge about the actual local value of [$?_W AET/?_W Q^*$].

B.10 Summary and conclusions.

The model described in **Appendix A** is a carefully researched implementation of the Penman-Monteith model of actual evapotranspiration, the Rutter interception model, and the Dupuit-Boussinesq equations for a horizontal, isotropic, and homogenous aquifer with fully-penetrating stream. The model structure and meteorological inference procedures are designed with the objective of studying hydrologic effects of vegetation conversion. Toward this end, the model has several novel features: 1. The canopy drainage parameter is indexed to canopy interception storage capacity (the latter is an independent parameter). 2. Rather than treating it as vegetation parameter, aerodynamic conductance is calculated as the product of vapor drag coefficient and wind speed. Vapor drag coefficient is calculated from momentum drag coefficient by taking into account excess resistance; momentum drag coefficient is calculated from turbulent diffusion theory, with momentum roughness length and zero-plane displacement indexed to canopy height. 3. The model uses Rossby Similarity Theory for neutrally-stable profiles to adjust windspeed for changes in momentum drag coefficient. 4. The aquifer hydraulic properties are expressed in terms of a parameter t_{90}, rather than hydraulic conductivity.

The model was forced with climate data from Seattle-Tacoma International Airport. Forest albedo and leaf area index were estimated from data collected at a mature forest in southwestern Washington. Apart from these, forest and shrub parameters were estimated from a variety of literature sources. Uncertainty intervals for shrub and forest seasonal latent heat fluxes were calculated. Fluxes were calculated for advection-free and advection-positive conditions. Local groundwater storage was simulated for a range of possible values of the aquifer parameter.

A surprising outcome of this exercise has to do with horizontal advection. The model predicts that a large contrast in surface roughness does not translate into a significant difference in the advectively-forced latent heat flux over wet vegetation. This is because the wind speed transvaluation scheme predicts that near-surface windspeed will *decrease* as vegetation roughness *increases*, and this factor offsets and nearly cancels the effect of increased aerodynamic drag. The model predicts that horizontal advection can produce very large increases in latent heat flux from wet canopy, but the magnitude of increase will be similar over tall and short vegetation. Finally the model predicts that horizontal advection produces only a modest increase in latent heat flux over dry canopy and over the course of the dry season. A major weakness of the simulation of horizontal advection over wet canopy was that the vapor pressure deficit was assumed to be the same over both vegetation covers. In fact, it is likely that vapor pressure deficit would tend to be lower over a wet clearing than over an upwind wet forest (McNaughton and Jarvis, 1983).

Two versions of the model—GAETP and GAETQ—were described. The versions are identical in every respect, except that GAETQ uses a calibrated rate parameter in place of the Penman source term in winter only. When winter advection is set to zero in GAETQ runs, direct evaporation proceeds at the rate EWP regardless of whether $Q^*(t)$ is posit, ive so that about half of winter season AET occurs nocturnally. In advection-free runs of GAETP, nocturnal evaporation is negligible, and $?_W$AET amounts to only about one-third of $?_W Q^*$.

The GAETQ latent heat flux results for forest compare favorably to observations made above a 50 year-old Douglas-fir stand on Vancouver Island. Except for $?_W Q^*$ being much lower, the climate there is similar to that of Puget Sound Lowland. The summer results for forest are also consistent with measurements of summer water use by a Douglas-fir tree (Fritschen, 1978). The predicted change in annual volume of recharge compares well to change-in-annual-water-yield results from paired catchment studies.

In terms of annual and seasonal water balance components (**Figure 2-3**), magnitude of maximum drought season soil water deficit (**Figure 2-4**), timing of autumnal rehydration of the rooting zone (**Figure 2-5**), and wet season profiles of local groundwater storage (**Figure 2-6**) and storage difference (**Figure 2-7**), the results are similar for three of the four parameter sets. The parameter set which produces results that stand apart is Shrub LOW_ET. The confidence intervals for these hydrologic variables are small in the case of forest, and are large in the case of shrub. The confidence interval for the hydrologic effects of vegetation conversion is large, not because of large uncertainty in forest simulations, but rather because of large uncertainty in the shrub simulations, and due to the large range assigned to t_{90}. The major source of uncertainty in simulated latent heat flux and groundwater recharge for shrub is lack of knowledge as to which version of the model should be used.

C Use of NCDC daily data as primary source of model input.

C.1 Introduction.

Long-term hourly time series of most of the meteorological variables required for GAET are available for nine locations in the state of Washington. These are Spokane, Walla Walla, Bellingham, Olympia, Seattle-Tacoma, Stampede Pass, Yakima, Whidbey Island, and Quillayute. A considerably more dense network of station data is provided by the National Climate Data Center (NCDC), but the NCDC data provides only 24-hour cumulative precipitation (**P24**), daily minimum air temperature (**T_{min}**), and daily maximum air temperature (**T_{max}**). A subset of stations provide snow accumulation in addition to these three variables. NCDC also has a sparse network of stations that provide precipitation and air temperature at hourly or 15-minute minute resolution. For use of the model as a screening tool, it would be of obvious advantage if the model could be forced with NCDC data, or with hourly variables inferred from the three NCDC variables.

C.2 Procedure.

The following procedure was devised for testing whether valid results can be obtained when the primary model input data is from an NCDC cooperator station.

1. Prepare a daily time series of P24, T_{min}, and T_{max} from the Seatac TMY2 data set.

2. Dissagregate P24, T_{min}, and T_{max} to hourly values.

3. Estimate hourly net radiation ($Q^*_{(t)}$).

4. Run the model in advection-free mode, with forest parameters, and with hourly net radiation, precipitation, and air temperature as estimated in steps 2 and 3. (For the advection-free run, relative humidity and windspeed are not required.)

5. Compare the seasonal values of latent heat flux obtained in step 4 with the results obtained when the TMY2 data is used as input.

In Step 2, hourly cumulative precipitation is equal to P24/24. A sine function was used to obtain hourly temperature by interpolation from T_{min} and T_{max}. For this interpolation, the T_{min} observation was assumed to occur at 6 a.m., and the T_{max} observation at 2 p.m., regardless of time of year.

For Step 3 it was decided to try to find a method for estimating global-horizontal shortwave radation at surface (**K_{in}**) from 24-hour precipitation and extraterrestrial shortwave radiation (**K_{ex}**), since the former is provided by the NCDC stations, and the latter depends only on latitude, julian day, and time-of-day, and can, therefore, be calculated for any location. TMY2 hourly values of K_{in} and K_{ex} were aggregated to a daily time step. These daily variables are denoted ? $_{(d)}K_{in}$ and ? $_{(d)}K_{ex}$, respectively, where the subscript d represents a particular day. It was found that the ratio [? $_{(d)}K_{in}$/? $_{(d)}K_{ex}$] has a mean value of 0.5 on days with no rainfall during sun-up hours, and 0.3 on other days. This observation suggests the following model for *hourly* net radiation:

[3-1a] $$Q^*_{(t)} = (1-\alpha)0.3K_{ex(t)} + L_{net} \text{ when } P_{(t)}=0$$

[3-1b] $$Q^*_{(t)} = (1-\alpha)0.5K_{ex(t)} + L_{net} \text{ when } P_{(t)}>0$$

C.3 Results.

[3-1] was tested at Wind River. The Wind River data set provides all four components of the radiation budget (i.e., incoming and outgoing shortwave and longwave radiation). Hourly Q* was *calculated* for autumn 1999 and autumn 2000 from the measured radiation components, i.e., as

[3-2] $$Q^*_{(t)} = K_{in(t)} - K_{out\ (t)} + L_{in\ (t)} - L_{out(t)},$$

where the four terms on the right hand side are measured. Q* was *estimated* with **[3-1]**, with L_{net} calculated from [2-2a,b] and albedo set to 0.08; K_{ex} was calculated at the latitude of the Wind River tower using equations from Bras (1990).The results shown in **Figure 3-1** appear to justify [**3-1**], except that the model coefficients appear to be slightly different at Wind River (i.e., the goodness-of-fit is better in Panel B, for which the coefficients differ from [3-1]).

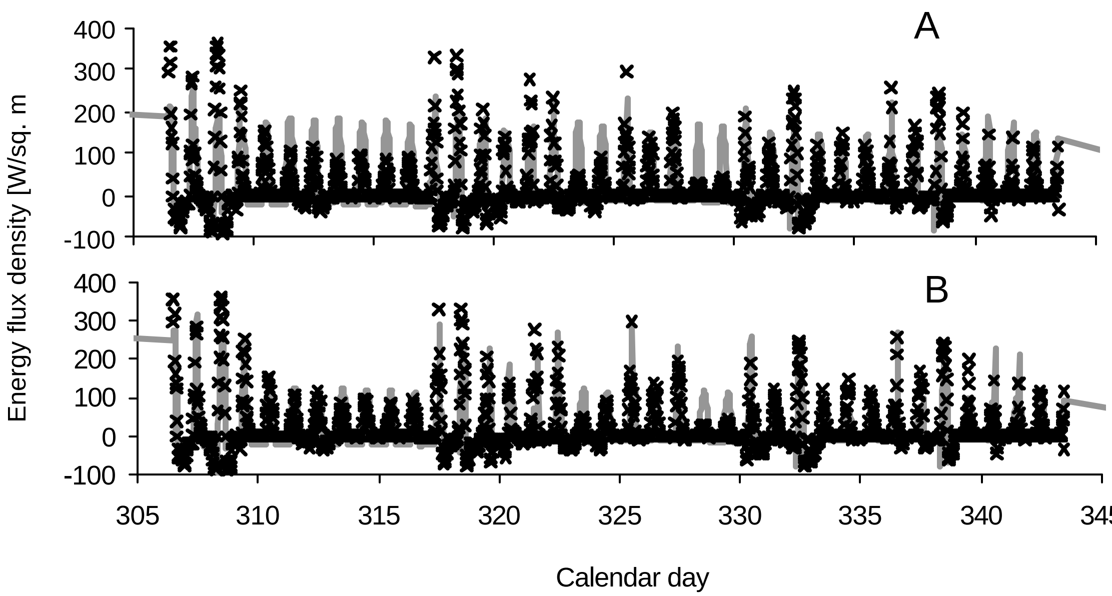

Figure 3-1. **Comparison of measured and estimate net radiation at the Wind River canopy crane. Panel A: Equation 3-1 (solid line) and measured (x). Panel B: Equation 3-1, except with coefficients if 0.6 and 0.2 in [3-1a] and [3-1b], respectively (solid line), and measured (x).**

For Step 5, five simulations were performed.

1. TMY2 hourly air temperature replaced with interpolated air temperature.

2. TMY2 hourly precipitation replaced with P24/24.

3. Q* estimated with [3-1] and L_{net} set to zero.

4. TMY2 air temperature substituted as in Run 1, and Q* estimated as in Run 3.

5. No substitutions for TMY2 data.

The fifth run is the contrul run. It was found that the diurnal and seasonal simulated latent heat flux is highly insensitive to the source of air temperature and Q*. That is to say, runs 1, 3, and 4 give very similar results to the control run. Winter latent heat flux was much higher in Run 2 than in the control run.

C.4 Discussion.

A number of runs were carried out for differing assumptions about the diurnal distribution of P24. These runs showed that winter latent heat flux is extremely sensitive to how precipitation is assumed to be distributed through a day. Winter interception loss is lowest (and winter transpiration loss is greatest) when P24 is assumed to occur as a one-hour night-time event. Winter interception loss is greatest (and winter transpiration loss is least) when P24 is assumed to be uniformly distributed over a full twenty-four hour period. Summer latent heat flux is only slightly sensitive to the diurnal distribution of precipitation.

For those parameter sets which use EWP in winter (i.e, the forest simulations, and the Shrub HIGH_ET simulation), the precipitation-distribution problem is solved simply by calibrating EWP *after* deciding upon the diurnal distribution of P24.

For the Shrub LOW_ET simulation, the Penman source term is retained as the estimator of radiation-forced potential evaporation. In this case, it is necessary to use an objective procedure for estimating an appropriate diurnal precipitation distribution, or else to only apply the model at locations where hourly precipitation data is available.

As discussed elsewhere in this report, it is not known whether EWP or the Penman source term should be used for estimating advection-free winter potential evaporation for shrub. If empirical data is obtained which shows that EWP should be used, then lack of knowledge about the diurnal distribution of P24 will no longer pose a significant source of uncertainty.

C.5 Conclusions.

The prospect for using daily NCDC data in place of detailed hourly data is promising. For GAETQ, detailed radiation data is not needed. Rather, a reasonably good estimate of cumulative winter net radiation is needed. A method will need to be developed for estimating this quantity at NCDC stations. For GAETP, diurnally-resolved radiation and precipitation data are required. For a small fraction of NCDC stations, fifteen minute and/or hourly precipitation data is available. At these stations, to estimate seasonal Q* (for GAETQ) and diurnally-resolved Q* (for GAETP) to sufficient accuracy might be achievable with [3-1]. It needs to be tested whether the coefficients of [3-1] are site-specific.

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A Model Description.

A.1 Introduction.

The model described here is tailored to the problem of simulating evapotranspiration for contrasting vegetation types, water table fluctuations, and groundwater discharge for locations where precipitation occurs as rain (rather than as snow or snowmelt). Direct evaporation of moisture stored on vegetation, transpiration, and discharge from a groundwater aquifer. This model is called “GAET” for groundwater and actual evapotranspiration simulation model. GAET is essentially an implementation of the Penman-Monteith equation, the Rutter interception model, and hydraulic ground water theory. Effort has been made to limit to a small number the required vegetation-dependent parameters, and to define these so that they may be estimated a priori. It is well-known that surface properties can have a profound effect on surface energy and water balances and on meteorology in the atmospheric boundary layer (André et al., 1989). In recognition of this fact, GAET includes algorithms for estimating meteorologic variables over forest, given observations over non-forest.

Given the intended application of this model, it was deemed unnecessary to include a realistic treatment of several aspects of the problem. The energy balance is calculated for horizontal surfaces having no terrain shading. The treatment of turbulent transport phenomena assumes near-neutral stability. GAET does not address the dynamics of surface runoff, shallow subsurface stormflow, and macropore flow. Groundwater is assumed to be entirely determined by local recharge and discharge, i.e., there is no intermediate and regional scale contribution to groundwater. Vertical travel time of infiltrate from soil surface to water table is instantaneous. Soil water viscosity effects on transpiration, subsurface water movement, and capillary rise are not addressed.

The ground water aquifer is assumed to behave as a deep Dupuit-Boussinesq ideal aquifer with fully penetrating stream (i.e., rectangular, horizontal, isotropic and homogenous). GAET includes equations for estimating water table profiles for the idealized Dupuit-Boussinesq aquifer. The value of this capabality is that it enables one to make slope stability calculations. It is not an objective of GAET to accurately simulate groundwater dynamics for a real system. Whether a particular real aquifer has a baseflow behavor resembling that of a Dupuit-Boussinesq aquifer is unimportant. The groundwater simulation capabilities of GAET have value for standardizing model output in a model-intercomparison or regional-intercomparison study. In particular, it allows one to control for aquifer properties in such intercomparison studies, so that slope stability or pore pressure calculations will differ as a result of differences in climate, vegetation parameters, soil parameters, and aquifer conductivity parameter. To expect simulated and observed water table profiles and groundwater discharge to show any resemblance is extremely optimistic. Likewise, using resemblance (or lack thereof) of observed and measured groundwater profiles and discharge as a model validation test is an excessively stringent and inappropriate criteria for assessing the validity of the evapotranspiration domain of the model.

A.2 Model structure and implementation: Overview.

The vegetation-dependent parameters are canopy height (**H_c**), canopy gap fraction (**GF**), albedo (a), leaf area index (**LAI**), minimum insolation for stomatal opening (**Q_sm**), minimum surface temperature for stomatal opening (**Tm**), cuticular resistance to vapor transport per unit of leaf area index (**r_{st}x**), canopy interception capacity (**Cx**), and rootzone available water capacity (**RZx**). The vegetation-independent parameters are infiltration fraction (**INF**), soil texture class, and aquifer recession constant (**K_b**). **INF** is the fraction of precipitation that reaches the ground surface and leaves the system as either groundwater outflow or transpiration, rather than being routed by a shorter pathway to the channel network.

The required meteorologic variables are the following: Gross precipitation (**P_g**), incoming shortwave radiation (**k_{in}**), incoming and outgoing longwave radiation (**L_{in}** and **L_o**), air temperature (**T_a**), vapor pressure deficit (**D**), and wind speed (**U**). If any of the required meteorologic variables are not provided at hourly resolution by the selected data source, then they must be estimated.

The major state variables are canopy water content, root zone water content, and stomatal conductance. Transpiration rate is calculated from the Penman-Monteith equation (**§A.3.1**). It is determined by meteorology (**§A.4)**, aerodynamic conductance (**§A.3.2)**, stomatal conductance (**§A.3.4**), and leaf area index (**§A.3.5**). Soil moisture tension also influences transpiration, but indirectly so, through an effect on stomatal conductance. Soil moisture tension is calculated from root zone water content and the Brooks-Corey equation, with Brooks-Corey parameters appropriate for the assumed soil texture (**§A.3.4**). Stomatal conductance is influenced by root zone water content, atmospheric vapor pressure deficit, and vegetation type. All precipitation to a patch of ground having a closed vegetation canopy is added to canopy storage. Water on the canopy is lost through drainage and evaporation (**§A.3.6**). The rate of evaporation of intercepted water from a fully wet canopy is calculated from the Penman equation (**§A.3.1**), and is determined by meteorology, surface roughness, and canopy water content. All precipitation is assumed to occur as rain—the model as yet has no provision for snow— and reaches the ground as direct precipitation in canopy gaps or as canopy drainage. Of precipitation that reaches the ground, a constant fraction (**INF)** is assumed to enter the root zone; the fraction [**1-INF**] is assumed to be routed away as surface and shallow subsurface runoff. Water in the root zone is lost through transpiration and by drainage to the groundwater aquifer (**§A.3.3**). Groundwater recharge occurs only when storage in the root zone would otherwise exceed field capacity. The groundwater aquifer is modeled as a lumped linear kinematic reservoir (**§A.3.8**).

Vegetation height determines surface roughness parameters. Surface roughness parameters, in turn, determine the momentum drag coefficient (**§A.3.2**), and are needed for the wind transposition scheme (**§A.4.4**). Aerodynamic conductance is not a vegetation parameter; rather, it is calculated as the product of vapor drag coefficient and wind speed (**§A.3.2**); vapor drag coefficient is a derived vegetation parameter. Leaf area index is needed to scale stomatal resistance up to canopy surface resistance (**§A.3.5**). The value used for Brooks-Corey parameters depend on soil texture. Soil texture categories are clay, sand, sandy-loam, and silty-loam.

A.3 Model description.

The simulation model is essentially an implementation of the Penman-Monteith equation for actual evapotranspiration from vegetated surfaces (Monteith, 1965).

A.3.1 Penman-Monteith equation.

Dry-canopy transpiration rate (**E_t**) is calculated as

[A-1] $$\lambda E_t(t) = [\Delta(t)Q(t) + c_{pa}\rho_a D(t)g_{aV}(t)]/[\Delta(t)+\gamma(1+\pi(t))].$$

Wet canopy evaporation rate (**E_p**) is calculated as

[A-2] $$\lambda E_p(t)= [\Delta(t)Q(t) + c_{pa}\rho_a D(t)g_{aV}(t)]/[\Delta(t)+\gamma].$$

where

> E is latent heat flux from a patch of surface area [LT^{-1}, e.g., mm/day];
> Q is available (radiant) energy flux density [e.g., MJ/m2/day];
> D is vapor pressure deficit [e.g., mbar or kPa];
> g_{aV} is aerodynamic conductance for vapor transport [LT^{-1}];
> π is equal to zero for a wet canopy and equal to g_{aV}/g_s for a dry canopy [dimensionless];
> g_s is canopy surface conductance [LT^{-1}];
> Δ is the slope of the saturation vapor pressure-temperature relationship [e.g., mbar/K]);
> c_{pa} is a constant (heat capacity of air at constant pressure, 987 J $kg^{-1}K$);
> ρ_a is a constant (density of dry air, 1013 kg m^{-3});
> λ is a constant (latent heat of vaporization, 2.5 MJ m^{-3}); and
> γ is a constant (psychrometric constant, 0.66 mbar/K).

[A-1] and [A-2] are identical except for the term ($1+\pi$) appearing in the denominator of [A-1]. [A-2] is also called the Penman equation; E_p is often called potential evaporation or Penman evaporation. E_t has units of mass flux density, which is to say, volume of water per unit surface area per time, or depth of water evaporated per time. Horizontal wind speed (**U**), Q, D, and air temperature (**T_a**) are the meteorologic forcing variables; wind speed and air temperature influence E_a through their effects on g_{aV} and Δ, respectively. In theory, Δ should be calculated at the mean of surface temperature (**T_s**) and T_a, but in practice it is usually calculated at T_a.

Over the temperature range -10°C to 40°C, λ, c_{pa}, ρ_a, and γ are, to a good approximation, physical constants; Δ is a physical constant for a given air temperature. λE and Q have units of energy flux density, and they can be positive or negative in sign. E is defined as positive when latent heat flows from surface to atmosphere, and negative when condensation is occurring. Q is defined as positive when it is directed to the surface. Q is positive most of the day, and usually negative at night. g_{aV} is largely determined by vegetation height and wind speed. It can be expressed as the product of wind speed and a drag coefficient $\boldsymbol{C_{aV}}$ for turbulent vapor transport (Jarvis et al., 1976). g_s is the plant resistance to water moving down a vapor pressure gradient from the leaf interior to the leaf exterior. Its value can fluctuate markedly within a single day. Variations in g_s tend to be correlated to soil water status, and meteorologic variables, but its value stays within a range that is characteristic of a species. The upper limit of the range, which I denote g_s^*, is obtained under optimal environmental conditions. I will use the symbol π^* to represent g_{aV}/g_s^*. Potential transpiration (**PT**) is the maximum possible transpiration rate for a plant or vegetation cover, for a given set of meteorologic conditions. It is given by [A-1] when π equals π^*.

$\mathbf{E_a}$ is the actual evapotranspiration rate from a canopy of any wetness status; it is a weighted mean of E_p and E_t:

[A-3] $$E_a(t) = E_t(t)\,(1-W(t)) + E_p(t)W(t),$$

where the weighting factor W is a state variable, and is a measure of degree of canopy wetness (see §A.3.6). It should be noted that E_t, E_p, and E_a are latent heat flux rates per unit *closed canopy* area. Assuming that latent heat flux from canopy gaps is small, latent heat flux rates per unit *landsurface* area are obtained by multiplying E_x (i.e., E_t, E_p, or E_a) by the factor 1-GF, where **GF** is canopy gap fraction.

A.3.2 Aerodynamic conductance.

Aerodynamic conductance can be expressed in terms of drag coefficient (Jarvis et al., 1976). The relationships between resistance (**r**), conductance (**g**), and dimensionless drag coefficient ($\boldsymbol{C_a}$) for an arbitrary scalar x are as follows:

[A-4] $$g_{ax}(t) = r_x(t)^{-1} = C_{ax}\,U(t).$$

where **U** is wind speed. Rather than treating g_{aV} as a vegetation-dependent parameter, as is sometimes done, I calculate C_{aV} and wind speed separately. The details of the wind speed transvaluation scheme are given in **§A.4.4**. The model calculates C_{aV} as a function of vegetation height ($\mathbf{H_c}$), screen height ($\mathbf{z_R}$), and $\ln[z_{oM}/z_{oV}]$:

[A-5] $$C_{aV} = \{\, \mathbf{k}^{-1} \ln[10z_R/H_c + 3.5] + \mathbf{k}^{-1} \ln[z_{oM}/z_{oV}] \,\}^{-2}$$

where **k** is von Karman's constant; $\mathbf{z_{oM}}$ and $\mathbf{z_{oV}}$ are the roughness lengths for momentum and vapor transport, respectively; and z_R is the distance from top-of-canopy to instrument sensor (Shuttleworth (1991) calls this *screen height*). The ratio z_{oM}/z_{oV} is often taken to be unity—in which case $\ln[z_{oM}/z_{oV}]$ equals 0—, but a value in excess of unity is probable, since vapor transport is not supported by pressure gradients, as is momentum (Shuttleworth, 1991). Garrat and Francey (1975) suggest that $\ln[z_{oM}/z_{oV}]$ equals 2.

[A-5] is obtained from the definitions for C_{aM} and C_{aV}, and assuming that z_{oM}/H_c and δ/H_c equal 0.1 and 0.65, respectively, where d is zero-plane displacement. The results of many micrometeorological studies, in which aerodynamic parameters have been derived empirically, support these assumptions about z_{oM} and δ for closed forest canopies of all types (Jarvis et al., 1976; Parker, 1995; Humphreys, 1999). These ratios do not show much sensitivity to wind speed.

The details of the derivation of [A-5] are as follows. The drag coefficient for momentum is

[A-6] $$C_{aM} = \{\mathbf{k}/[\ln[(z\text{-}\delta)/z_{oM}]\}^2,$$

where **z** is height of instrument sensors above ground level (z_R=z-H_c). C_{aM} is undefined for z < $\delta+z_{oM}$, and has a value of zero at z = $\delta+z_{oM}$. $\delta+z_{oM}$ is typically at about 75 percent of canopy height above ground (Jarvis et al., 1976). Shuttleworth (1991) calls $\delta+z_{oM}$ the "effective sink-source height" for the idealized canopy (i.e., the 'big leaf') described by the Penman-Monteith model. z_R and z both refer to the height at which a flux (momentum, heat, or water vapor) is measured or calculated. If wind speed and humidity sensors are at different elevations, then these data must be adjusted to a common z_R. Instrument sensors are usually placed between 2 to 10 m above canopy.

δ and z_{oM} have been determined empirically for many vegetation covers, and the typical results are z_{oM}=0.1H and δ=0.65H_c, with only weak dependence on wind speed being found. Humphreys (1999) obtained this result for a Douglas-fir stand on west Vancouver Island, Canada. Assuming z_{oM}/H and δ/H equal 0.1 and 0.65, respectively, and replacing z with z_R+H_c, [A-6] becomes

[A-7] $$C_{aM} = \{\mathbf{k}/\ln[10z_R/H_c + 3.5]\}^2,$$

By analogy to momentum drag, drag coefficients for heat (C_{aH}) and mass transport (C_{aV}) are assumed to exist and to have the same form as [A-6], but are assumed to differ in the roughness length parameter ($\mathbf{z}_{oH}$ for heat and $\mathbf{z}_{oV}$ for vapor):

$$C_{aV} = \{\mathbf{k}/[\ln[(z\text{-}\delta)/z_{oV}]\}^2 = \{\mathbf{k}/[\ln[(z\text{-}\delta)/z_{oM}(z_{oM}/z_{oV})]]\}^2$$

$$C_{aH} = \{\mathbf{k}/[\ln[(z\text{-}\delta)/z_{oH}]\}^2 = \{\mathbf{k}/[\ln[(z\text{-}\delta)/z_{oM}(z_{oM}/z_{oH})]]\}^2$$

The rightmost expressions for C_{aV} and C_{aH} show clearly the relationship of these drag coefficients to C_{aM}. Empirical studies show that $z_{oH} = z_{oV}$ (and C_{aV}=C_{aH}) is a reasonable assumption but that $z_{oM}/z_{oV} > 1$. C_{aV} can be expressed in terms of C_{aM} and z_{oM}/z_{oV}:

$$C_{aV}^{-½} = \mathbf{k}^{-1}\ln[(z\text{-}\delta)/z_{oM}(z_{oM}/z_{oV})]$$

$$= \mathbf{k}^{-1}\ln[(z\text{-}\delta)/z_{oM}] + \mathbf{k}^{-1}\ln[z_{oM}/z_{oV}]$$

$$= C_{aM}^{-½} + \mathbf{k}^{-1}\ln[z_{oM}/z_{oV}]$$

Finally, [A-5] is obtained by substituting the right-hand-side of [A-7] into the immediately preceding expression.

A.3.3 Soil moisture accounting.

The soil moisture model has a single state variable: **RZ** [L^1]. This represents root zone water content and is equal to the difference in moisture contents at field capacity and wilting point. The only soil moisture model parameter is **RZx** [L^1]. RZx represents maximum plant-available moisture in the rooting zone (volume per unit plan area); the latter is rooting depth times the difference in moisture contents at field capacity and wilting point. Change in root zone water content is simply equal to net precipitation less transpiration, less excess storage. Excess storage is the only source for groundwater, and is discharged to the groundwater aquifer during the subsequent time step. RZ is updated at the end of each time step as follows:

[A-8] $$RZ_{(t)} = INF\, P_{n(t)}\, \Delta t - (1\text{-}GF)\,(1\text{-}W_{(t)})E_{t(t)}\, \Delta t - q_{R(t)}\, \Delta t,$$

where

[A-9] $$P_{n(t)} = (1\text{-}GF)D_{c(t)} + GF\, P_{g(t)},$$

[A-10] $$q_{R\,(t)} = \max\,[RZ_{(t-\Delta t)} - RZx,\, 0]/\Delta t,$$

$\mathbf{P_n}$ is net precipitation rate, $\mathbf{q_R}$ is root zone discharge rate, $\mathbf{P_g}$ is gross (above-canopy) precipitation rate, $\mathbf{D_c}$ is drainage rate per unit area of *closed* canopy, **W** is relative canopy wetness [dimensionless], D**t** is the model timestep, **INF** is the fraction of direct throughfall plus canopy drainage that infiltrates to the root zone or groundwater reserviors—i.e., the fraction of net precipitation that is *not* routed to the channel system via surface and shallow subsurface pathways—, GF is gap fraction [dimensionless], and $GF\,P_g$ is the area-average rate for direct throughfall rate, where direct throughfall refers to precipitation that falls to the ground without interacting with the canopy. All of the rate variables (P_n, q_R, P_g, E_t, and D_c) have units of L^1T^{-1}, and INF, W, and GF are dimensionless (0=INF=1, 0=GF=1). P_n and q_R are calculated for *landsurface* area. The coefficient (1-GF) is applied to E_t and D_c because these rate variables are calculated for closed canopy. D_c and W are calculated by the canopy interception model (§A.3.6). The mathematical form of the stomatal resistance function ensures that transpiration demand approaches zero as the root zone becomes desiccated.

A.3.4 Stomatal conductance [g_{st}].

Stomatal resistance ($\mathbf{r_{st}}$) is the reciprocal of stomatal conductance. Tan and Black (1976) showed that diurnal and day-to-day variations in stomatal resistance for thinned and unthinned Douglas-fir stands on eastern Vancouver Island, Canada in summer were at least moderately correlated to vapor pressure deficit and soil moisture tension, but not to insolation and stem density. In particular, the sensitivity to vapor pressure deficit increased as soil moisture tension increased. The dense salal understory in the thinned stand showed much weaker sensitivity to these meteorologic variables, and usually had higher conductance at any given time than did the overstory. The understory contributed substantially to the total plot transpiration when soil moisture status was good, despite its lower leaf area index and sheltered position.

Stomatal resistance is calculated with the equations given in **Table A-1**, unless Q_s =Q_sm and T_s=Tm, in which case resistance r_{st} is set to **r_{st}x**, a vegetation parameter. This represents canopy surface resistance for a leaf area index of unity, when stomata are fully closed. **Q_sm** and **Tm** are vegetation-dependent parameters, Q_s is incoming shortwave radiation, and T_s is surface temperature (§A.4.1). Q_sm and Tm represent the minimum values for incoming shortwave radiation and air temperature, respectively, that are required for stomatal opening to occur. The regression equations in Table A-1 were fitted by Tan et al. (1978) to data presented by Tan and Black (1976). These equations contain soil suction pressure and vapor pressure deficit as independent variables.

Table A-1. **Stomatal resistance regression equations.**

Vegetation	Reference[a]	Formula[b]	Applicability[c]	R^2
Douglas-fir	7a	$\exp(1.4581 + 0.0027\ D^2)$	$-3.5 = \Psi_s < 0$	0.54
Douglas-fir	7b	$\exp(1.9901 + 0.0034\ D^2)$	$-9.5 = \Psi_s < -3.5$	0.84
Douglas-fir	7c	$\exp(2.6906 + 0.0057\ D^2)$	$-12.5 = \Psi_s < -9.5$	0.18
Salal[d]	8a	$\exp(1.4418 + 0.0019\ D^2)$	$-3.5 = \Psi_s < 0$	0.24
Salal	8b	$\exp(1.7436 + 0.0031\ D^2)$	$-9.5 = \Psi_s < -3.5$	0.69
Salal	8c	$\exp(2.1768 + 0.0027\ D^2)$	$-12.5 = \Psi_s < -9.5$	0.02

[a]Refers to numbered equations in Tan et al., 1978.
[b]Expression gives r_{st} in s cm^{-1}; D is vapor pressure deficit in bars (10 millibars ~ 1 kPa).
[c]Ψ_s is soil suction pressure in bars (1000 millibars=101.3 kPa =one standard atmosphere).
[d]Salal is the common name for a broadleaf evergreen shrub.

To use the regression equations in Table A-1, it is necessary to relate the model state variable RZ to soil suction pressure (Ψ_s). The Brooks-Corey equation (Brooks and Corey, 1966) provides a means to do this:

[A-11] $$\theta_{e(t)} = [BC1/\Psi_{s(t)}]^{BC2},$$

where **BC1** and **BC2** are regression parameters; θ_e is effective saturation [dimensionless]; Ψ_s and BC1 must be in similar units. Solving for Ψ_s and using RZ/RZx in place of θ_e:

[A-12] $$\Psi_{s(t)} = BC1[RZx\ /\ RZ_{(t)}]^{1/BC2}.$$

Suitable values for the parameters BC1 and BC2 for different soil types are given in **Table A-2**.

Table A-2. **Soil hydraulic parameters**[a].

soil type	Ksat[cm/s]	BC1[b]	BC2[c]
clay	3.4E-05	90	0.44
silty loam	3.4E-04	45	1.2
sandy loam	3.4E-03	25	3.3
sandy	8.6E-03	15	5.4

[a]**Bras, 1990**, page 352, Table 8.1.
[b]Represents air entry pressure in cm water. 1 mbar = 1.033 cm water column height
[c]Dimensionless. Physical interpretation is pore size distribution index.

Ψ_s is calculated at each time step with [A-12]. Stomatal resistance is calculated using the appropriate regression equation in Table A-1. The choice of which equation to use at each time step depends on vegetation cover and suction pressure. For evergreen needle-leaf forest I use the Douglas-fir regression equations. For evergreen and deciduous shrub, I use the salal regression equations. Soil texture is specified prior to initiating a model run and this determines the values used in [A-12] for the parameters BC1 and BC2.

A.3.5 Canopy surface conductance.

Leaf area index (LAI; [L^2 L^{-2}]) is used to scale stomatal conductance up to canopy surface conductance. Stomatal conductance (g_{st}) represents the canopy surface conductance (g_s) for a canopy with leaf area index of unity. Stomata are considered to behave like resistors acting in parallel; therefore, canopy surface resistance ($r_s = g_s^{-1}$) is calculated as

[A-13] $\quad r_{s(t)} = r_{st(t)}/LAI,$

or, equivalently,

[A-13] $\quad g_{s(t)} = g_{st(t)}\,LAI.$

A.3.6 Interception loss.

Direct evaporation of intercepted water per unit closed canopy area (WE_p) [$(L^3T^{-1})(L^{-2}) = LT^{-1}$] is modeled with the following equation:

[A-14] $\quad dC_{(t)}/dt = P_{g(t)} - W_{(t)}E_{p(t)} - D_{c(t)},$

where C is canopy water content [L], P_g is above-canopy (gross) precipitation rate [LT^{-1}], E_p is potential evaporation rate [LT^{-1}] and is calculated with [A-2/2-2], W is the canopy wetness function [LT^{-1}], D_c is drainage rate [LT^{-1}], and W E_p is the direct evaporation rate. [A-14] is the Rutter interception model. It must be applied at a short time step (e.g., 2 minutes) in order to give good results, since the direct evaporation rate WE_p influences and is influenced by canopy storage. Notice that GF (gap fraction) does not appear in [A-14], but does appear in [A-8] and [A-9]. The reason is as follows: $dC_{(t)}/dt$, D_c, E_p, and E_t and refer to closed canopy, whereas P_g and P_n (and also q_R) refer to a unit of landsurface area.

Cumulative interception loss (**IL**) per unit landsurface area between time t_1 and t_2 is

[A-15] $$IL = (1\text{-}GF)\left[?_0^{t2} W_{(t)}E_{p(t)}\, d\tau - ?_0^{t1} W_{(t)}E_{p(t)}\, d\tau\right].$$

W in [A-3], [A-8], and [A-15] is modeled as follows:

[A-16] $$W_{(t)} = C_{(t)}/Cx \text{ if } C_{(t)} = Cx, \text{ else } 1.0,$$

where **Cx** [L] is canopy interception storage capacity (i.e., volume of water in storage divided by canopy surface area [L^3/L^2]). Cx is not the maximum amount of water that may be stored on the canopy at any time; rather, it is the value of storage above which drainage is non-negligible. During bouts of intense rainfall, C may exceed Cx. Cx also represents the maximum amount of between-storm interception loss. Cx is the effective depth of stored on a canopy that must be attained before drainage becomes significant; likewise, drainage becomes negligible when $C/Cx < 1.0$. D_c is modeled as follows:

[A-17] $$D_{c(t)} = 0.2\ hr^{-1}\ Cx\ e^{3.22\,(C(t)/Cx - 1)}.$$

The derivation of [A-17] is given in **§A.3.7**. It is not unusual in hydrologic simulation models to omit the drainage term, in which case, water is not allowed to accumulate on the canopy in excess of canopy interception storage capacity (e.g., Wigmosta et al., 1994 and Sias, 1997). In such models, P_n=0 unless C =Cx and P_g>E_p.

A.3.7 Canopy drainage function.

Rutter (1972) proposed and tested the following expression for drainage:

[A-18] $$D_{c(t)} = a \exp(b\, C_{(t)})$$

where **a** [LT^{-1}] and **b** [L^{-1}] are regression parameters. Here it is necessary to relate the parameters a and b to vegetation characteristics. I achieve this by first defining two variables D_δ and D_x. D_x is the drainage rate when canopy interception store is equal to storage capacity (i.e., when C equals **Cx**). D_δ is the drainage rate when canopy interception store is equal to $(1+\delta)$ **Cx**, with $\delta > 0$. According to [A-18/3-16],

[A-19a] $$D_x = a \exp(b\, Cx),$$

[A-19b] $$D_\delta = a \exp(b\,(1+\delta)Cx).$$

From [A-19a] and [A-19b] it follows that

[A-20a] $b = \ln[D_\delta / D_x] / [\delta\, Cx]$,

and

[A-20b] $a = Cx\, [D_x / Cx]\, \exp(-b\, Cx)$.

Substitution of these expressions for a and b into [A-18/3-16] yields

[A-21] $D_{c\,(t)} = Cx\, [D_x / Cx]\, \exp(b\, C_{(t)} - b\, Cx)$.

The greatest generality is achieved by treating $[D_x/Cx]$ and $[D_\delta / D_x]$ as vegetation-independent parameters so that the drainage function is entirely specified for a specific vegetation cover by the value of the parameter Cx. $[D_x/Cx]$ and $[D_\delta / D_x]$ can be estimated from a plot of drainage rate versus canopy storage for any vegetation cover, and then applied to any other vegetation cover. Calder and Wright (1986) provide such a plot for two similar Sitka spruce forests in the United Kingdom. The estimated intercepton storage capacity for these stands is 2.0 mm. Canopy water content measurements were obtained by means of a calibrated radiometric procedure which they devised. These workers fitted a modified Rutter function to their data:

[A-22/3-20] $D_{c\,(t)} = 0.013 \text{ mm hr}^{-1} \left(e^{1.71 \text{ mm}^{-1} C(t)} - 1\right)$

(Calder and Wright, 1986). Their modification ensures that drainage is zero when canopy storage is zero. Their fitted function gives a drainage rate of about 0.4 mm hr^{-1} when storage is 2.0 mm, and 2 mm hr^{-1} when δ=0.5 (C=3 mm). Based on this result, the model values for $[D_x/Cx]$ and $[D_{0.5} / D_x]$ are set to 0.2 hr^{-1} and 5.0, respectively. Substituting these values into [A-20a] and [A-21] yields $b = 3.22 / Cx$ and

[A-17] $D_{c\,(t)} = 0.2 \text{ hr}^{-1}\, Cx\;\; e^{3.22\,(C(t)/Cx - 1)}$.

This is the expression given in **§A.3.6** for the drainage function in the canopy water balance. **Figure A-1** shows [A-/3-15] for Cx=2.0 mm and Cx=0.5 mm. Notice that for Cx=2.0 mm, the model values for $[D_x/Cx]$ and $[D_\delta / D_x]$ give a drainage function that is quite close to [A-22]; a and b calculated from [A-20a,b] are 0.016 mm hr^{-1} and 1.61 mm^{-1}, respectively. These are not too different from the parameters in [A-22]. For Cx =0.5 mm, the model drainage function yields a=0.004 mm hr^{-1} and b=6.44 mm^{-1}.

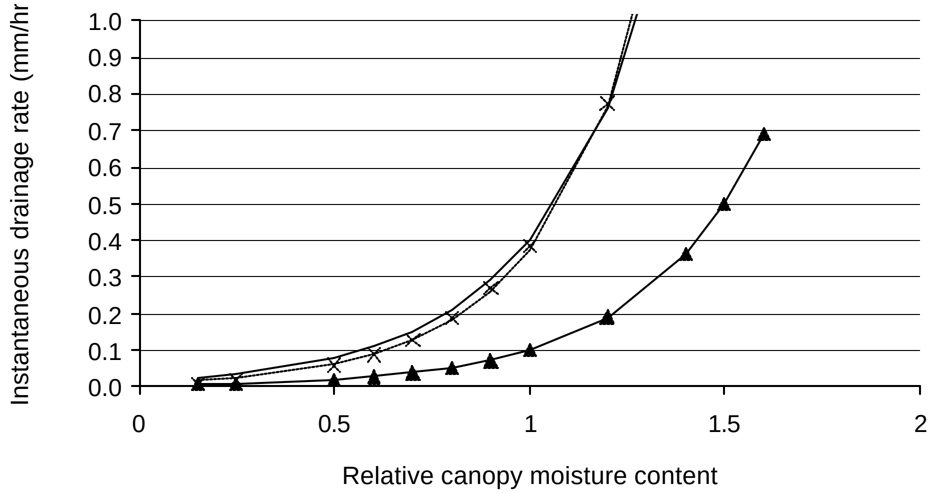

Figure A-1**. Drainage function examples ([A-17]) for $[D_x / Cx] = 0.2\ hr^{-1}$ and $[D_{0.5} / D_x] = 5.0$: Cx = 2.0 mm (solid line, no symbol); Cx = 0.5 mm (solid line, filled triangles). Calder and Wright (1986) fitted drainage function (symbol X, no line – see text); [A-21] with parameters chosen to give a good fit to Calder and Wright's fitted function (dashed line): {Cx = 1.90 mm, $[D_x / Cx] = 0.2\ hr^{-1}$, and $[D_{0.5} / D_x] = 6.0$]}.**

A.3.8 Groundwater aquifer dynamics.

Recharge occurs at the base of the root zone only when infiltration of moisture from the surface into the root zone would otherwise cause the root zone moisture content to exceed field capacity. For conservation of mass under the conditions that a) the only source of influx is recharge, b) the only sink is groundwater discharge, and c) the travel time of root zone overflow to the water table is zero, the governing equation is

[A-23] $$dS_{(t)}/dt = (1/A)\, dV_{(t)}/dt = q_{V(t)} - q_{g(t)},$$

where **S** [L] is volume (**V**) of water in storage at time t divided by aquifer plan area **A**; $\mathbf{q_V}$ is specific groundwater recharge rate$[LT^{-1}]$, and $\mathbf{q_g}$ $[LT^{-1}]$ is specific groundwater discharge rate. Groundwater recharge occurs when infiltration causes soil moisture content in the root zone to exceed field capacity (see **§A.3.3**):

[A-24] $$q_{V(t+Tv(t))} = q_{R(t)},$$

where

[A-25] $$T_{V(t)} = f\,[D\text{-}H_{(t)}, q_{V(t)}, ...].$$

and where $\mathbf{T_V}$ is the travel of a wetting front from the base of the root zone to the water table, **H** is the height of the water table (phreatic surface) above base elevation, and **D**-H is the vertical distance from the phreatic surface to the base of the root zone. Although [A-25] does not admit diffusion of the wetting front, this could be taken into account if desired. Notice that $q_{V(t)} = q_{R(t)}$ if the root zone discharge is assumed to arrive at the phreatic surface instantaneously. The form and full list of independent variables in [A-25] are not specified here, as it is expected that the importance of T_V to groundwater dynamics is best explored through sensitivity analysis.

Assuming the aquifer behaves as a lumped linear kinematic reservoir, then $q_g=K_bS$. As shown by Brutsaert and Nieber (1977), K_b [T^{-1}] is the recession constant and depends in material properties and aquifer size. Such an aquifer has the same behavoir as the idealized horizontal Dupuit-Boussinesq aquifer described in Brutsaert and Nieber (1977). Its outflow hydrograph declines exponentially between recharge events, and has a characteristic shape.

For the special case that recharge is constant during a finite time step Δt, the exact solution to the ordinary differential equation

[A-26] $dS_{(t)}/dt = q_{V(t)} - K_b S_{(t)}$

is

[A-27] $S_{(t+\Delta t)} = S_{(t)}\exp(-K_b \Delta t) + q_{V(t)}(K_b \Delta t)^{-1} (1-\exp[-K_b \Delta t])$.

Using hydraulic groundwater theory, it is possible to deduce the water table profile $\mathbf{H}_{(x,t)}$ of an idealized aquifer from the simulated time series S. For example, for the case of a horizontal Dupuit-Boussinesq aquifer having a cosine-form water table profile immediately upon cessation of recharge,

[A-28] $H_{(x,t)} = 0.5p\ S_{(t)}\ n_e^{-1}\cos[(p/2)(x/B)]$

and

[A-29] $q_{g(t)} = 0.5\ K_bB^2\ n_e[S_{(t)}/S_{o(t)}]$,

where $\mathbf{n_e}$ is the aquifer effective drainable porosity, $\mathbf{S_o}$ is the storage at the moment recharge ceased (i.e., most recently prior to time t), **B** is aquifer breadth (i.e., distance from divide to seepage face), and **x** is distance from seepage face ($H= 0.5p\ S\ n_e^{-1}$ and 0 at the divide and the seepage face, respectively). [A-28] and [A-29] are valid between, but not during recharge events. [A-28] and [A-29] were obtained by assuming that S/n_e is the average water table depth along the profile. Being able to convert simulated storage to a water table profile means that one could derive a time series of pore pressures along a slip face from model output.

A.4 Transvaluation of meteorologic variables.

Many of the simulations in this report will use detailed hourly meteorologic data from the National Solar Radiation Database (NSRDB). These data consist of measured and modeled data, and provide—except for longwave radiation, surface temperature, and gross precipitation—all of the variables required to calculate evapotranspiration with the Penman-Monteith equation.

Contemporaneous co-located precipitation data is available separately from the National Climate Data Center (NCDC). The NSRDB and NCDC measurements come from National Weather Service (NWS) stations at airports. Presumably the airport data is representative of conditions over clearing or short vegetation. The problem arises then as to what the meteorologic conditions would have been at the same location had the vegetation instead been forest, and had NWS instruments been situated above the forest canopy. For lack of a better term I will use *transvaluation* to mean the procedure of estimating meteorologic variables over forest from meteorological measurements made within a nearby clearing. (The Random House College Dictionary defines transvalue as "to reestimate the value of, especially on a basis differing from accepted standards; reappraise, reevaluate.")

Pearce et al. (1980) showed that forest evapotranspiration at a site in New Zealand would be overestimated by 30 percent if meteorologic data is taken from a clearing. McNaughton and Jarvis (1983) discuss theoretical aspects of this problem in some detail. To model surface-atmosphere interactions is well beyond the scope of this project. It is necessary for this project, however, to make a reasonable attempt to account for these effects. The present problem requires transvaluation of vapor pressure deficit, wind speed, net radiation, and near-surface temperature. Precipitation and air temperature are assumed to be vegetation-independent.

The appropriateness of the term transvaluation arises from the following conceptualization of the situation. I conceive the NSRDB data as being representative of an extensive patch of homogenous flat terrain. The NWS meteorologic station is *assumed* to be positioned with adequate fetch in all directions. Downwind of the NWS station are leading edges of infinitely-long adjacent strips of forest and grassland. The strips are aligned with the prevailing wind direction, so that the leading-edge meteorology is the same for both strips, and is the same as that of the NWS station. There is no heat, momentum, and mass transfer across the boundary between the strips. To further simplify the situation, I assume that the vegetation of the grassland strip is identical to that of the NWS station; therefore, I need only make adjustment to the NSRDB data for the forested strip. In particular, I want to know the meteorology far enough downwind of the forest leading edge, so that—to use terminology from Perrier and Tuzet (1991)—the *internal equilibrium sublayer* has attained the height of the *surface flux layer*, i.e., the meteorological profiles above the forest have fully adjusted to the new surface, meteorological variables are no longer are changing in the downstream direction, and the horizontal divergences of the surface energy fluxes and meteorologic variables are zero. I assume the transvaluation schemes I describe below give me the equilibrium values for the meteorologic variables over forest, and which are consistent with those at the NWS station and over grassland.

A.4.1 Surface temperature and near-surface air temperature.

Near-surface air temperature (T_n) is defined here as the mean of the canopy surface temperature (T_s) and the air temperature (T_a) at screen height. T_n is the temperature at which Δ in [A-1] and [A-2] is calculated. Canopy surface temperature of the 'big leaf' (Shuttleworth, 1991) is an abstract scalar, and apparently has three meanings: It is the temperature of water within stomatal cavities averaged over the total transpiring leaf surface area of the canopy; it is the average temperature of all water adhering to the canopy leaf surfaces; and it is the effective radiative temperature of the canopy. According to the third definition, T_s can be calculated from measured outgoing longwave radiation (or L_o can be calculated from T_s), provided that canopy surface emissivity is known or can be estimated.

André et al. (1989) presented numerical 3-D atmospheric boundary layer model results for a fine summer's day in France. Their model performed well when compared to meteorological measurements. Their analysis shows little difference in nighttime net radiation, suggesting that outgoing longwave and surface temperature was similar for the two covers. In daytime, net radiation was somewhat higher for forest. In spite of this, and in spite of the forest having a higher mean air temperature for the atmospheric boundary layer (ABL), the forest surface temperature was 2°C cooler than agricultural land. Jarvis et al. (1976) report that needle-leaf forest surface temperature is usually close to air temperature. The findings of Jarvis et al. (1976) and André et al. (1989) can be understood as follows: Needle-leaf forest absorbs a greater portion of the incoming radiant energy (longwave plus shortwave); the total energy available to the forest exceeds that available to cropland, so that the *sum* of the sensible and latent heat flux over forest is larger than over cropland. When soil moisture is not limiting, both sensible *and* latent heat flux (not just their *sum*) will be larger over forest. Due to the forest having considerable surface roughness at both the canopy and the leaf/branch scales, the sensible heat emanating from the forest canopy is efficiently mixed within the full depth of the ABL, and the canopy radiative temperature is close to (screen-height) air temperature; air temperature is, in turn, close to the mean temperature of the ABL. Despite cropland having lower sensible and latent heat flux than nearby forest, the air temperature over cropland is substantially higher than the mean temperature of the ABL, due to the fact that the sensible heat produced at the cropland surface is *not* well-mixed within the full depth of the ABL. For short broadleaf vegetation, the canopy surface temperature will exceed the air temperature.

It is beyond the scope of this project to model the vegetation-dependent surface radiative temperature, as this would require a canopy energy balance model. Instead, I evaluate through sensitivity analysis how large the difference between T_s and T_a would have to be to make a significant difference to the predicted evapotranspiration contrast. For the purpose of sensitivity analysis I define four parameters:

$D\mathbf{T_{aF}} = T_{aF} - T_{aM};$
$D\mathbf{T_{aG}} = T_{aG} - T_{aM};$
$D\mathbf{T_{sF}} = T_{sF} - T_{aF};$
$D\mathbf{T_{sG}} = T_{sG} - T_{aG};$

where D**T** (subscript implied) is the temperature differential sensitivity parameter, and where subscripts a,s, M, F and G refer to air, surface, meteorologic station, forest, and grassland, respectively. From the definition already given for near-surface temperature, it follows that

[A-30] $$T_{nF} = T_{aM} + \Delta T_{aF} + \Delta T_{sF}/2$$

A similar equation exists for near-surface air temperature over grassland. If the above interpretation of Jarvis et al. (1976) and André et al. (1989) is correct, then it seems justified to assume that $\Delta T_{aF} < 0$, $\Delta T_{sF} = 0$, $\Delta T_{aG} = 0$, and $\Delta T_{sG} > 0$. Whether the surface radiative temperature needs to be better characterized will be explored through sensitivity analysis.

A.4.2 Available radiant energy.

The surface available radiant energy budget can be written

[A-31] $$Q_{(t)} = R_n(t) - \Sigma J(t) = (1-\alpha)(\tau_a(t))S_o(t) + L_{in}(t) - \varepsilon \sigma_B T_s(t)^4 - \Sigma J(t),$$

where R_n is net radiation, ΣJ represents heat storage fluxes (into and out of soil, biomass, and canopy air space) and energy consumed in photosynthesis, S_o is extraterrestrial shortwave irradiation, α is surface broadband albedo, τ_a is atmospheric transmissivity to S_o, L_{in} is incoming longwave radiation, ε is surface emissivity, σ_B is the Steffan-Boltzman constant $[E^1L^{-2}T^{-1}{}^\circ K^{-4}]$, and T_s is surface temperature. α, ε, and τ_a are dimension less and have values between zero and unity. Q, R_n, J, and S_o have units of energy flux density $[E^1L^{-2}T^{-1}]$. S_o is determined entirely by time of day, time of year, and latitude. It has a value of 1346 W m^{-2} at noon on the Equinox at the equator. The term containing T_s represents outgoing longwave radiation (L_o). τ_a depends solar zenith angle, cloud type and cover, and atmospheric particulate and water vapor content.

ΣJ has been determined experimentally for some forested plots. While it may be a major term in the daily and shorter term energy budget for forest, empirical results show that ΣJ can be neglected in seasonal budgets without much loss of accuracy. τ_a and L_{in} can be surface-dependent, since atmospheric water vapor content, cloud cover extent and opacity, and cloud base temperature can be influenced by surface latent heat flux. Forest/grassland differences in L_{in}, τ_a, and ε are probably small compared to the magnitude of Q, so these are assumed to be surface-independent meteorologic variables. The net radiation budget for forest and grassland will differ because of having different values for albedo and, on summer days, different surface and near-surface temperature (see **§A.4.1**).

A.4.3 Vapor pressure deficit.

McNaughton and Jarvis (1983) describe a protocol for transvaluation of vapor pressure deficit. Their procedure is to infer the free stream potential vapor pressure ($\mathbf{D_o}$) from surface roughness and a near-surface measurement of D. The inference procedure is then inverted to calculate near-surface D for a different surface roughness. McNaughton and Jarvis performed such a calculation for vapor pressure deficit. They suggest that vapor pressure deficit over forest (D_F) will be equal to about 0.76 of the value over a clearing (D_G). Their discussion of the problem of vapor pressure transvaluation is oriented toward growing season. The model default assumption is D_F/D_G=0.75 at every timestep.

A.4.4 Wind speed.

Rossby similarity theory (see Rowntree, 1991) is used to calculate wind speed over an alternative vegetation cover from a measured or assumed wind speed for a reference surface. Rossby similarity theory assumes near-neutral stability and a fully-developed turbulent boundary layer;

for this situation, the wind profile has a predictable logarithmic shape within the boundary layer, i.e.,

[A-32] $$U_{(z,t)} = U_{*(t)}\, \mathbf{k}^{-1} [\ln[(z-\delta)/z_{oM}] = U_{*(t)}\, C_{aM}^{-1/2},$$

where U_* is friction velocity (defined for the logarithmic profile of a fully-developed turbulent boundary layer), and other symbols have already been defined. [A-6] gives C_{aM} in terms of screen height and vegetation height. The gradient of the velocity profile (dU/dz), the friction velocity, and the boundary layer thickness depend on the surface roughness length for momentum and the free-stream wind speed $\mathbf{U_o}$. Free-stream wind speed is the time-averaged horizontal wind speed in the prevailing wind direction and above the elevation at which the wind speed profile is affected by the surface.

The procedure is analagous to that described by McNaughton and Jarvis (1983) for transvaluation of vapor pressure deficit. Let the subscripts 1 and 2 represent the original and alternate vegetation covers, respectively. The first step is to use [A-32] to calculate U_{*1}. Next, $U_{o(t)}$ is calculated from $U_{*(t)1}$ and $z_{oM,1}$:

[A-33] $$U_{\mathbf{o}(t)} = U_{*(t)1}\, \mathbf{k}^{-1} [\{\ln[U_{*(t)1}\,(fc\ \ z_{oM,1})^{-1}] - A\}^2 + B^2]^{1/2},$$

where **fc** is the Coriolis parameter (10^{-4} sec^{-1} at 44 degrees latitude; 10^{-5} sec^{-1} at 4 degrees latitude), and **A** and **B** are fitted parameters (**Table A-3**). [A-33] is Rowntree's (1991) equation [2.20] solved for U_o. Next, a binary search procedure is used to find $U_{*(t)2}$, given $U_{o(t)}$ and $z_{oM,2}$. Finally, wind speed at height z_R above the new canopy is calculated from $U_{*(t)2}$ and [A-32]. This completes the transvaluation of wind speed.

Table A-3. **Fitted parameters for near-neutral stability.**

A	B	Source
1.07	5.14	Arya(1975)[a]
1.9	4.7	Deacon(1973)[b]
1.2	2.3	P.J. Mason[c]

[a]Arya(1975), cited by Rowntree (1991).
[b]Deacon(1973), cited by Rowntree (1991).
[c]Theoretically derived; cited by Rowntree as personal communication from P.J. Mason.

Rowntree (1991) found low sensitivity to A,B pairs for $z_{oM}<1$ m, and modest sensitivity for z_{oM} = 1 m (10-15%). The default model values are A=1.2 and B=2.3.

A.5 Model Behavior.

A.5.1 Canopy interception.

The Rutter interception model ([A-18]) has two parameters. The canopy interception model has been formulated as a Rutter interception model, but in such a way as to reduce the number of independent parameters to one. Furthermore, the model is formulated so that the required parameter represents canopy interception storage capacity (Cx). The utility inheres in the fact that there exists a great deal of literature that attempts to empirically define appropriate values for Cx for different types of canopies. The literature shows that Cx is tends to be larger for forest canopies than for short vegetation and crops. The objective here is two show how the canopy interception model behavior differs for contrasting values of Cx.

For purpose of this demonstration, precipitation event is defined according to absence of non-negligible canopy drainage. **Figures A-2** and **A-3** demonstrate the behavior of the canopy model for two different values of canopy interception storage capacity (Cx), for a 17 mm precipitation event that that is 28 hours in duration. The mean hourly evaporation rate for the event is 0.11 mm. The first two of three peaks in the net precipitation traces is smaller for the larger value of Cx, and the tail of the trace is longer. This figure illustrates how, according to the Rutter interception model, a vegetation canopy acts like a water storage reservoir, in that the outflow hydrograph fluctuations are dampened compared to fluctuations in the inflow hydrograph: The gross precipitation and net precipitation traces correspond to inflow and outflow hydrographs, respectively, and the reservoir capacity (Cx, in this case) determines the dampening effect of the reservoir on flow fluctuations. Despite the different traces for the two covers, there is no difference in event total net precipitation (14 mm) and event total evaporation (3 mm).

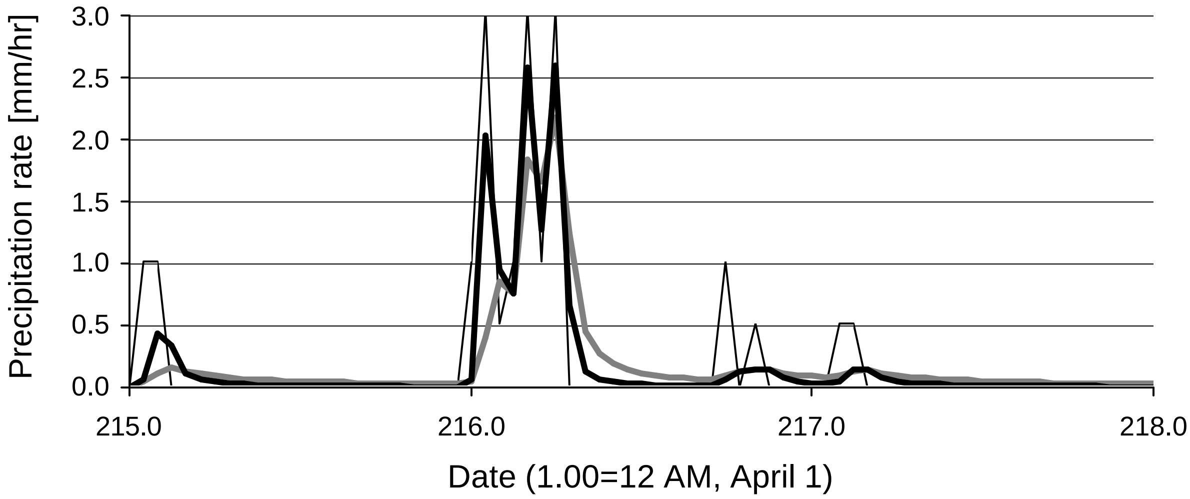

Figure A-2**. Gross and net precipitation rates for a rain event that begins on day 215 (Oct. 31), for two values of Cx. Gross precipitation (thin black line); net precipitation for Cx=3.0 mm (thick gray line); net precipitation for Cx=1.0 mm (thick black line).**

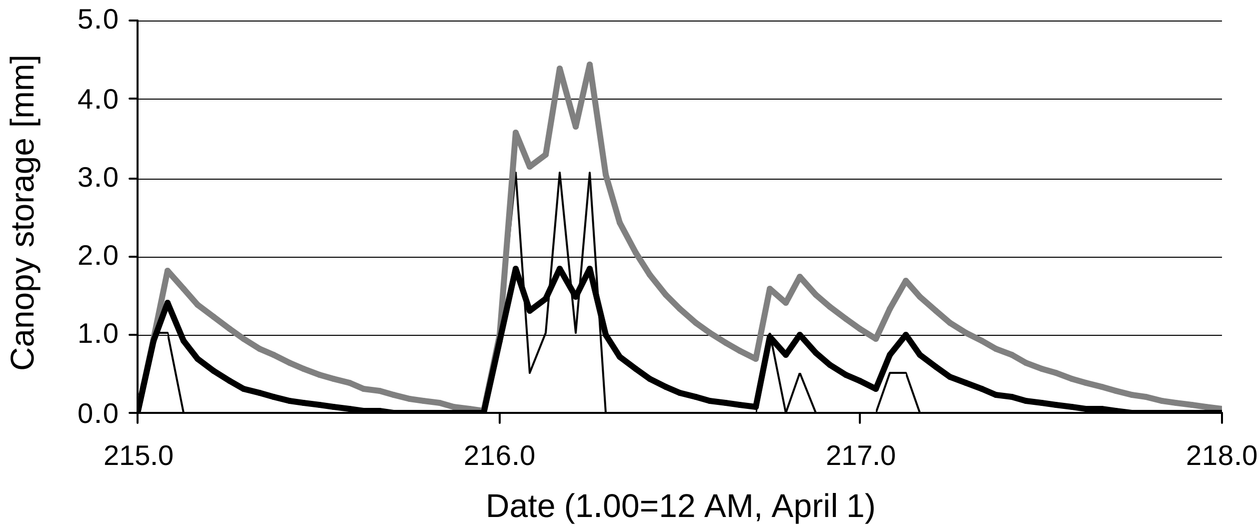

Figure A-3. **Time series of canopy storage for two values of Cx, for the same event shown in Figure A-2: Cx=3.0 mm (thick gray line); Cx=1.0 mm (thick black line).**

A.5.2 Wind speed transvaluation scheme.

The purpose of the wind speed transvaluation scheme (**UTS**) is to obtain estimates of wind speed at a downwind location $u_{h(t)}$, given observed wind speed ($u_h^o{}_{(t)}$). The subscript h refers to instrument height in meters. The assumptions in the UTS entail that windspeed will differ at the downwind location only if the momentum roughness parameters ($\mathbf{z}_{oM}$ and d_o) differ from those at the reference surface ($\mathbf{z}_{oM}^o$ and d_o^o). The roughness parameters for the downwind location are referenced to canopy height (H_c), i.e., $\mathbf{z}_{oM}$ and d_o are set to $0.10H_c$ and $0.67H_c$, respectively. Geostrophic windspeed ($U_{g(t)}$) showed little sensitivity to $\mathbf{z}_{oM}^o$ over the range 1.0×10^{-4} m to 0.05 m. This range is probably inclusive of the effective surface roughness at Seatac. Drag coefficient (C_D), mean wind speed at 2 m above canopy (u_2), and aerodynamic conductance for momentum (g_{aM}) are given in for three values of H_c (**Table A-4**).

Table A-4. **Wind speed transvaluation example.**

H_c[a]	C_D	u_2	g_{aM}
0.2	0.0036	5.1	1.86
2.0	0.0076	3.5	2.6
40	0.0140	2.56	3.6

[a]See text for definitions of symbols.

C_D is a canopy property, since it depends only on H_c and the assumed relationships between H_c, $\mathbf{z}_{oM}$ and d_o. Mean wind speed is modestly sensitive to canopy height. C_D increases with canopy height, while u_2 decreases. g_{aM} increases with height, but half as quickly as C_D.

The UTS predicts that for a given reference surface windspeed at time t, wind speed at 2 m above short vegetation ($u_{2(t)}$) will *exceed* $u_{2(t)}$ over tall vegetation. If this is not taken into account, which is to say if one assumes $u_h(t)$ is not affected by vegetation cover, then the ratio of aerodynamic conductances for the two covers is independent of windspeed, is temporally invariant, and will equal the inverse of the drag coefficient ratio. Consider the situation that net radiation is zero, and canopies are fully wetted. The relative latent heat flux over tall and short vegetation in this circumstance is determined by the relative aerodynamic conductance. If windspeed is assumed to be the same over both canopies, then the latent heat flux over a 2.0 m canopy is 0.54 (i.e., 0.0076/0.0140) of that over 40 m canopy. If, on the other hand, the surface roughness effect is taken into account, then the relative latent heat flux over the 2.0 m canopy is 72 percent of that over the 40 m canopy. This percentage increases as the estimated geostrophic windspeed increases.

This constitutes a theoretical argument that large differences in surface roughness do not necessarily lead to large differences in advectively-forced wet canopy evaporation rates. This has implications for estimating hydrologic effects of vegetation conversion in locales where wet season horizontal advection is not insignificant. This effect is not relevant to dry season effects of conversion, since dry season latent heat fluxes are moisture-limited.

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B Nomenclature.

Units: dimensionless ("1"), length ("L"), time ("T"), temperature ("K"), energy ("E"), pressure ("P")

Physical constants (see text for values and units)

dt	time step
c_{pa}	heat capacity of air at constant pressure
ρ_a	density of dry air
γ	psychrometric constant
λ	latent heat of vaporization
k	von Karman's constant
S_o	Solar constant
σ_B	Stefan-Boltzmann constant
fc	Coriollis force

Regression parameters

BC1	$[K^1]$	air entry pressure (Brooks-Corey model)
BC2	[1]	pore-size distribution index (Brooks-Corey model)
A, B		Rossby Similarity Theory parameters

Vegetal and geologic parameters

z_R	$[L^1]$	screen height
H_c	$[L^1]$	canopy height
GF	[1]	gap fraction
α	[1]	albedo
LAI	[1]	leaf area index
$Q_s m$	$[E^1 T^{-1} L^{-2}]$	insolation threshold for stomatal opening
Tm	$[K^1]$	temperature threshold for stomatal opening
$r_{st}x$	$[T^1 L^{-1}]$	cuticular resistance to transpiration
Cx	$[L^1]$	canopy storage capacity (volume per unit area)
RZx	$[L^1]$	root zone moisture storage capacity (volume per unit area)
INF	[1]	infiltration fraction
K_b	$[T^{-1}]$	baseflow recession constant
n_e	[1]	Aquifer effective porosity

Derived parameters

δ	$[L^1]$	Zero-plane displacement
z_{oM}	$[L^1]$	Momentum roughness length
z_{oH}	$[L^1]$	Vapor roughness length
C_{aM}	[1]	Drag coefficient for momentum transport
C_{aV}	[1]	Drag coefficient for vapor transport

Sensitivity parameters

D_F/D_G	[1]	Ratio of D over forest to D over grassland
$\ln(z_{oM}/z_{oV})$	[1]	Garrat-Francey ratio
ΔT_{aF}	$[K^1]$	Air temperature elevation (versus observed value) for forest
ΔT_{aG}	$[K^1]$	Air temperature elevation (versus observed value) for grassland
ΔT_{sF}	$[K^1]$	Surface temperature elevation (versus observed value) for forest
ΔT_{sG}	$[K^1]$	Surface temperature elevation (versus observed value) for grassland
T_V	$[T^1]$	Wetting front vertical travel time through vadose zone

State variables

C	$[L^1]$	canopy moisture content (volume per unit crown area)
W	[1]	relative canopy wetness
IL	$[L^3L^{-2}]$	cumulative interception loss
g_{st}	$[L^1T^{-1}]$	stomatal conductance
g_s	$[L^1T^{-1}]$	canopy surface conductance
r_{st}	$[T^1L^{-1}]$	stomatal resistance
r_s	$[T^1L^{-1}]$	canopy surface resistance
π	[1]	g_{aV}/g_s, r_s/r_{aV}
RZ	$[L^1]$	rootzone water content (volume per unit area)
ψ_s	$[P^1]$	root zone moisture tension
θ_e	[1]	relative saturation in rootzone
H	$[L^1]$	groundwater aquifer saturated depth
S	$[L^1]$	Volumetric water content of aquifer divided by aquifer plan area

Independent forcing variables

P_g	$[L^1T^{-1}]$	gross precipitation rate
k_{in}	$[E^1T^{-1}L^{-2}]$	downwelling shortwave radiation flux density
L_{in}	$[E^1T^{-1}L^{-2}]$	downwelling longwave radiation flux density
T_{aM}	$[K^1]$	dry bulb (air) temperature at screen height, measured value
D	$[P^1]$	vapor pressure deficit at screen height
U	$[L^1T^{-1}]$	windspeed at screen height

Derived forcing variables

K_{cc}	$[E^1T^{-1} L^{-2}]$	Clear sky downwelling shortwave radiation flux density
K_{in}	$[E^1T^{-1} L^{-2}]$	Downwelling global horizontal shortwave radiation flux density
L_{net}	$[E^1T^{-1} L^{-2}]$	Net longwave radiation flux density (positive incoming)
L_{in}	$[E^1T^{-1} L^{-2}]$	Upwelling longwave radiation flux density
L_o	$[E^1T^{-1} L^{-2}]$	Downwelling longwave radiation
Q^*	$[E^1T^{-1} L^{-2}]$	Available radiant energy (positive incoming)
τ_a	[1]	Atmospheric transmissivity
T_a	$[K^1]$	air temperature (adjusted from T_{aM} if assumed vegetation differs from actual)
T_s	$[K^1]$	Surface temperature
T_n	$[K^1]$	Near-surface temperature
U_*	$[L^1T^{-1}]$	Profile friction velocity
U_o	$[L^1T^{-1}]$	Free stream wind speed
Δ	$[P^1 K^{-1}]$	slope of the saturation vapor pressure versus temperature curve
g_{aV}	$[L^1T^{-1}]$	aerodynamic conductance for vapor transport
r_{aV}	$[T^1L^{-1}]$	aerodynamic resistance for vapor transport
$\mathring{a}_{PT}$	[1]	Priestley-Taylor coefficient for well-watered plants in absence of advection

Prognostic variables $[L^1T^{-1}]$

E_a	Actual evapotranspiration rate
E_p	Potential (wet canopy) evaporation rate
E_t	Transpiration rate
E_{eq}	Equilibrium evaporation rate
α_{eq}	Radiation partitioning coefficient ($E_{eq}=\alpha_{eq} Q^*$)
β	Bowen ratio
β_{eq}	Equilibrium bowen ratio
a_{PT}	E_a/E_{eq} (Priestley-Taylor coefficient)
P_n	Net precipitation rate
D_c	Canopy drainage rate
q_R	Root zone discharge rate
q_v	Ground water aquifer recharge rate
q_g	Ground water aquifer discharge rate

Acronyms

AET	$[L^1]$	Actual evapotranspiration (cumulative)
PE	$[L^1T^{-1}]$	Potential evaporation rate
PT	$[L^1T^{-1}]$	Potential transpiration rate
IL	$[L^1]$	Interception loss (cumulative)
ABL		Atmospheric boundary layer
TMY2		Typical Meteorological Year 2
NCDC		National Climate Data Center

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C Peer Review

The peer review process was adopted by the Cooperative Monitoring, Evaluation, and Review Committee (CMER) to insure that quality of research conducted by CMER met professional standards as judged by knowledgeable and objective third-person reviewers. To this end the Scientific Review Committee (SRC) was established at the University of Washington. After thorough review by the sponsoring scientific advisory group (SAG) and by CMER, project designs and reports are submitted to the SRC upon the recommendation of the sponsoring SAG and the concurrence of CMER. Upon the return of the SCR review, the SAG considers the review and responds appropriately. The SAG response is documented.

The final submittal of the reviewed report to CMER has been long delayed. The final report was submitted to the Upslope Scientific Advisory Committee on October 2, 2002, and the report and review documents (Appendix C1) were submitted to the SRC for review on March 21, 2003. The SRC reviews (Appendix C2) were returned to CMER on June 26, 2003 and the author's response to those reviews finalized on December 2, 2003 (Appendix C3).

UPSAG concludes that Ms. Sias' response to the SRC comments are appropriate and adequately addresses SRC issues. UPSAG believes their inclusion as Appendix C3 along with the SRC review comments in Appendix C2 provides an overall picture of the state of knowledge in 2003. With documents the reader should understand the strengths and limitations of the model presented in the report. As the SRC reviewers note, insufficient data were available at the time of the study (2002) to validate the model. To completely address SRC validation concerns additional studies are required. These studies have been outlined in Ms. Sias' response (Appendix C3).

C.1 Submittal Documents

C.1.1 Transmission Letter

TRANSMITTAL OF INFORMATION FOR TECHNICAL REVIEW

To: Dr. Dan Vogt, Managing Editor, Adaptive Management Scientific Review Committee (University of Washington/Washington State University)

From: CMER Upslope Processes Science Advisory Group (UPSAG)

Through: Geoffrey McNaughton, Adaptive Management Program Administrator

Date: March 21, 2003

Please find enclosed four (4) copies of a technical report we wish to submit for technical review by the Scientific Review Committee. Summary information is included below.

Document for review:

> Sias, Joan. September 15, 2002. Estimation of a multi-season evapotranspiration within humid temperate forest lands in relation to vegetation cover. I. Analytical assessment and model description. Prepared for the Upland Processes Science Advisory Group of the Cooperative Monitoring Evaluation and Research (CMER) Committee.

UPSAG Technical Contact:

Robert Palmquist

Northwest Indian Fisheries Commission

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Olympia, WA 98516-5540

(360) 438-1181, Ext. 379

bpalmquisy@nwifc.org

Attachments:

1. Background for review from Upslope Processes Science Advisory Group.

2. Review document:

> Sias, Joan. September 15, 2002. Estimation of a multi-season evapotranspiration within humid temperate forest lands in relation to vegetation cover. I. Analytical

assessment and model description. Prepared for the Upland Processes Science Advisory Group of the Cooperative Monitoring Evaluation and Research (CMER) Committee.

C.1.2 Background Document

BACKGROUND FOR REVIEW OF:

Sias, Joan. September 15, 2002. *Estimation of a multi-season evapo-transpiration within humid temperate forest lands in relation to vegetation cover. I. Analytical assessment and model description.* Prepared for the Upland Processes Science Advisory Group of the Cooperative Monitoring Evaluation and Research (CMER) Committee.

1. Context for Review

The evapotranspiration model developed/refined in this study is an outgrowth of an earlier model applied to the Hazel landslide. UPSAG contracted with Joan Sias to refine her earlier version to determine if timber harvest could affect soil recharge and destabilize deep-seated landslides. The model is intended to be site-specific. However, this first phase of model development does not have site specificity. The model described in this report covers the atmospheric and forest components to the extent the data will permit. To achieve site-specificity, additional data and refined soils and hydrogeological components are required in the model.

As model refinement progressed, the changing expectations of UPSAG and the realities of data availability, required several changes to the original scope of work. These changes are documented below to provide a basis for your review. The included report is not intended for submission to a scientific journal.

Scope of original contract dated March 16, 2001 - Background - Sias (1997) applied the Penman-Monteith equation to perform a continuous (year-round) simulation of evapo-transpiration and ground water recharge in the vicinity of the Hazel landslide (Stillaguamish River, near Darrington, WA). The model results indicated that winter evapo-transpiration may be a major component of the annual water budget for a forest, and is considerably reduced by timber harvest. This is a significant change over the conventionally accepted theory that winter evapo-transpiration is NOT important. The overall goal of this proposal is to subject the work of Sias (1997) to critical peer review. This proposal consists of two parts that can be carried out independently.

The major weaknesses of Sias (1997) are three-fold:

1) Incorrect implementation of Rossby similarity theory for estimating aerodynamic resistances for different vegetation covers [Rowntree, 1991];
2) Use of the Tmin/Tmax method to estimate vapor pressure deficit in winter [Hungerford, and others, 1989];
3) Assumption that meteorological variables over forest are the same as at the nearest climate station [Pearce and others, 1980].

Parts I and II of this proposal address the first and second weaknesses, respectively. Neither Part I nor Part II will address the third weakness, which constitutes a very difficult problem, and probably requires the application of a spatially explicit numerical weather prediction model.

The need to validate the Tmin/Tmax method is avoided in Part I by limiting analysis to NOAA stations (see Study Sites, below). This precludes Darrington as a study site (and therefore also precludes a re-analysis of the Hazel landslide). Darrington will, however, be included as a study site in Part II.

Objectives, Part I: To prepare and submit a scientific manuscript for peer review in order to:

a) Present and defend an a priori parameterization of the Penman-Monteith equation for application to continuous multi-year simulation (at sub-daily time-step) of vegetation-mediated moisture flux over forested and cleared lands in a temperate humid climate;

b) Present model results for at least two NOAA (National Oceanic and Atmospheric Administration) (hourly-reporting) meteorological stations in western Washington.

Objectives, Part II: To prepare and submit a scientific manuscript for peer review to

a) Validate the Tmin/Tmax method for estimating vapor pressure deficit in winter.

b) Present model results for at least two NCDC (National Climate Data Center)(daily-reporting) meteorological stations in western Washington, one of which must be Darrington, WA.

Changes made to original contract, approved by UPSAG and effective per DNR on August 31, 2001

The period of performance was extended through November 30, 2001 and the Part II task list was changed:

PART II TASK LIST

1. Use WRCCF (Wind River Canopy Crane Facility) data [contains short wave and long wave data] set to develop regressions for estimating components of the energy budget from short wave radiation.
2. Run the model with the SeaTac airport hourly data [contains short wave data and cloud cover information; represents grassland].
    a. Quantify the uncertainty in the model predicted energy budget contrast for forest vs. grassland, and how this translates into uncertainty in the contrast of radiative-forced AET and groundwater profiles.
    b. Quantify the uncertainty in the energy budget magnitude when the only available data is daily precipitation, maximum and minimum air temperature (as at NCDC station).

2. Intended Applications of Report Results

Background - There are a number of issues within Forests & Fish that question the effects of canopy removal on groundwater. Most urgently, the issue of how this effect may define groundwater recharge areas in glacial deep-seated landslides is important in assessing the potential as a high-hazard landform requiring Class IV Special processing. However, there is no accepted technique for assessing these areas. This project critically tests a preliminary model (developed by Joan Sias (1997)) used to determine if local groundwater effects from canopy removal occur. It examines the application of the model in terms of the deep-seated issue, UPSAG intends to use the model to identify those deep-seated landslides in glacial material where harvest on its recharge area of may elevate groundwater levels and promote failure. A site-specific assessment method would couple the model with current slope stability analytical techniques to evaluate the potential for movement of the landslide due to harvest.

3. Recommendations for Qualifications of Reviewers

Reviewers should be published in the field of hydrology and hydrologic modeling. Reviewers should be familiar with the analytic techniques used in this project.

4. Key Review Questions:

a. Is the design and execution of the project consistent with the original proposal and subsequent revisions to the scope of work (as detailed in Section 1 above)?
b. Is the design and execution of the project consistent with accepted scientific methodology?
c. Were the model parameters and their values appropriately assigned? If not, what parameters and values should have been used?
d. Are conclusions consistent with results?
e. Are methods and results consistent with the scope of work and future applications?
f. Is any information missing that is necessary to evaluate the results of the project?
g. Is this original work? Is there similar or parallel work that is not cited?

5. Additional Review Questions:

The project is a model requiring assumptions and simplifications that possess greater or lesser degrees of uncertainty. The committee and author have the following questions about these assumptions and simplifications and their uncertainties.

Model Features:

We request that the following model features are specifically assessed by the SRC with respect the questions that follow:

- Model structures (§A.3)
- Meteorological inference procedures (§A.4, §2.2.2)
- Implementation assumptions (§1.3.2)
- Parameter values (Table 2.2 in §2.3, Table 1 – 1)

a. Are any of the listed model features both (a) weakly justified and (b) strongly influential with respect to significant results? (Examples?)
b. Should any of the results or conclusions be considered more uncertain than described in the report because of a weakly justified model feature?

c. Would the simulated effect of forest harvest on wet season groundwater dynamics have been different if a particular model feature had been treated in a more defensible manner?
d. Are all of the major sources of uncertainty identified and adequately addressed?
e. Do the model results indicate that further research on this topic would lead to a method for identifying deep-seated landslides that could be destabilized by timber harvest?

References

Monteith, J.L., 1965, Evaporation and environment, *Symp. Soc. Exp. Biol.*, vol. 19, pp. 205-234.

Sias, Joan C., 1997. "Simulation of Groundwater Recharge at Hazel in Relation to Vegetation Cover," Part I of Miller, Daniel J. and Joan C. Sias, 1997. Environmental Factors Affecting the Hazel Landslide, Level 2 Watershed Analysis Report. Washington Department of National Resources, Northwest Region, Sedro Woolley, Washington.

C.2 Scientific Review Committee Review

The SRC consists of four persons – the ediot and three reviewers selected by the editor for their expertise in various aspects of the study. Each reviewer submits a review and the three reviews are summarized by the Editor and the major issues highlighted. These documents are presented here beginning with the Editors summary.

C.2.1 Editor's Summary

Dennis P. Lettenmaier
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June 26, 2003

Professor Daniel Vogt
Managing Editor, CMER Reviews
College of Forest Resources Box 352100
University of Washington
Seattle, WA 98195-2100

Dear Dan:

RE: "Estimation of multi-season evapotranspiration in relation to vegetation cover from regions with rainy-winter/dry-summer climate" by Joan Sias

Enclosed are three reviews of this report. It is clear from the reviews that each of the reviewers read the report carefully. There is no point in reproducing the specifics of the reviews here, but there are some major points that demand particular attention. Although the review form does not ask for specific recommendations, my interpretation of all three reviews is that the equivalent of "major revisions" in the terminology used by most journals will be required before this report can be useful to the client.

Reviewer A states, "… the work suffers from a major flaw …". As detailed by the reviewer, the perceived flaw is the introduction of a parameter (EWP) that facilitates a match of simulated and observed evapotranspiration. The reviewer argues that the problem is much more likely traceable to the use of meteorological data from Seattle-Tacoma airport, which is at least 100 km distant from the field site. Also, the author has prescribed relative humidity throughout the winter season as 100%, which is a demonstrably inaccurate assumption. There are now methods that allow transfer of meteorological data based on local conditions, and furthermore, it is almost certain that there are data records at or near the field site that could be used. Perhaps even a few years ago the difficulties in accessing climate data justified use of remote index sites, but this is no longer the case. Various data sets now exist that provide the forcings required to run land surface models. Among others is the Land Data Assimilation System (LDAS) project, which provides surface forcing data over most of North America. Another data set has been assembled by Peter Thornton (now at NCAR), which is applicable over most or all of the western U.S. I am inclined to agree with the reviewer that modifying the Penman-Monteith equation, which has been widely tested and applied globally, with an arbitrary factor is not defensible.

Reviewer B addresses each of the review questions posed quite literally. Some of the points raised are not major issues in my estimation – for instance, comparison of forest with evergreen shrub rather than grassland is, I believe, quite justifiable. However, other points are more substantive, for instance the comments that the report's conclusion that winter ET is non-negligible for evergreen needle-leaf forest is not well substantiated. The 1997 report is not peer-reviewed, and can hardly be used as a justification. The issue of winter ET has major implications for CMER, and in fact directly or indirectly was the motivation for the study, this issue needs to be resolved. Given the criticism of the modeling approach by the reviewers, it does not appear that a credible argument can at present be based on the model results. The reviewer's comments on model features deserve careful attention as well. Apparently the soil moisture accounting scheme is a very crude one, by the standards of modern land surface models. It's hard to understand why the author did not start with an accepted land surface scheme, of which many are around (see for instance various reports of PILPS – Project for Intercomparison of Land-Surface Parameterization Schemes). To me, it would have made far more sense to start with a credible land surface scheme, and then focus on its evapotranspiration algorithm, with particular focus to evergreen temperate forests. It is worth noting that many of these models user some variation of the Penman-Monteith algorithm.

Reviewer C states, "In its current form, however, the model contains some poorly-justified assumptions and inadequate validation for use as a general management tool". The main technical points questioned by the reviewer are the assumption of 100% relative humidity in winter (noted also by Reviewer A) and the calibration via an arbitrary adjustment factor of potential evapotranspiration (also noted by the other reviewers). The reviewer feels, and I concur, that these assumptions may well have resulted from attempts to tune the model to a specific data set (which is not necessarily representative of the field observations), and may have masked more fundamental problems with the model.

Overall, the reviewers have gone through the report very carefully, and have uncovered what I believe are some fundamental deficiencies. At this point, it is not clear how best to proceed. If this were a journal submission, my recommendation probably would be "reject with encouragement for resubmission". It is clear from the reviews that the results are not presently usable in a management context. On the other hand, the work may provide the basis for improved management in the future – but only with considerably more analysis, which I am assuming is not funded under the contract that supported this work. As indicated above, I do question the need to develop a model specific to the PNW, as there has been a good bit of hydrologic modeling work done that should be applicable, and would in any event serve as a better starting point.

Sincerely
Dennis P. Lettenmaier
Associate Editor
Professor of Civil and Environmental Engineering

C.2.2 Reviewer Comments

C.2.2.1 Reviewer A

C.2.2.2 Reviewer B

C.2.2.3 Reviewer C

Dennis Lettenmaier
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Dear Dr. Lettenamier:

Thank you for the opportunity to review "Estimation of multi-season evapotranspiration in relative to vegetation cover . . .", by Joan Sias.

The manuscript presents a discussion of the possible effects of forest harvest on annual and seasonal ET (EvapoTranspiration). In general the formulation of the base model (basically the Penman-Monteith Equation) is correct and clearly presented.

Unfortunately, the work suffers from a major flaw, which is described below under "Major Concerns" that prevents any conclusions to be drawn as to the significance of forest harvest effects on ET. Answers to the specific questions of the review committee are presented in the sections "Key Review Questions" and "Additional Review Questions", other comments are given in the section entitled "Comments". Please feel free to contact me with any questions regarding this review.

Major Concerns:

As part of model development, the author has introduced a new parameter (EWP) to modify the Penman Monteith (PM) equation because the author's initial simulation results with the classic PM model did not match observations. However, it is far more likely that misuse of the base meteorological data has necessitated this parameter. Basically, the author has attempted to use hourly observations from SeaTac airport to simulate the meteorology above a mature forest canopy in the Puget Lowlands (which are then compared to the lowlands of Vancouver Island, BC.) To accommodate for the fact that the forest in question receives considerably more precipitation than that measured at SeaTac, the author has doubled the precipitation at SeaTac without any adjustment of radiation or humidity. The values of ET simulated using these met data were then compared to observed ET over a mature forecast on Vancouver Island (a much wetter and significantly more humid location) and it was found that the PM model greatly overestimated or underestimated total ET depending on the assumptions made regarding winter Relative Humidity. When the author set winter RH to a constant 100%, the PM equation greatly underestimated ET, however when the author used the observed RH at SeaTac, the PM equation greatly overestimated ET. It is not surprising that straightforward application of the PM equation using SeaTac meteorology (including

RH) would overpredict total ET over a forest on Vancouver Island. However to correct for this "overprediction", the author chooses to instead force winter RH over the canopy to be 100% (thereby removing the effect of the vapor pressure deficit term of the PM equation) and then incorporate an "EWP" parameter that introduces a steady state source term into the calculation of Potential Evapotranspiration (PET) in the PM equation. In effect the author has calibrated a revised version of the PM equation to the Vancouver island data, then the results from this calibrated model are compared to the classic formulation of the PM equation for shrub land. This is an apples to oranges comparison.

The author argues that the "constant 100% RH during the winter" is required to limit "horizontal advection" because the Vancouver Island instruments were located to minimize "horizontal advection." However, this statement is not supported by the data from Vancouver Island, which clearly show long periods of time during winter when RH is below 100% above the canopy (Figure 1). During these periods, a vapor pressure deficit will form and the intercepted water from the canopy will evaporate. There is no need for the EWP parameter and hence there is no need for the modified form of the PM model. The unmodified PM equation (coupled with the authors simple interception model) contain sufficient parameters for calibration to the Vancouver Island data.

This reviewer feels strongly that the author should rerun the model simulations using the classic form of the PM equation on the actual Vancouver Island met data (The author would refer to this as a GAETP simulation under strongly advective conditions). The reviewer has downloaded these data and they are of sufficient quality for the purpose of conducting these simulations. All results and conclusions should then be drawn from these new simulation results. The results from the modified PM formulation (referred to as GAETQ) should not be presented in the final report. As the report is currently written, there is a great deal of confusion and uncertainty (admitted by the author) due to the two formulations of the PM equation. Removing this uncertainty will result in a greatly improved report and much clearer discussion. (although both will need to be rewritten as the model results will change significantly).

A second major concern is the author's choice of the TMY2 data set, which is designed to represent an average year, to simulate forest conversion effects that are expected to produce landslides. Obviously landslides occur during the wettest years, not during a typical year. Given a satisfactory response to the major concern above, the conclusions of a revised paper will be greatly strengthened if the author simulates a number of years, with at least some of them being extremely wet. This also relates to the authors finding based on a number of studies that Winter ET is about 100 mm. If we assume that winter ET from shrub is 0mm (unlikely), then the maximum increased infiltration to the soil is 100mm, independent of how wet a given year is. Thus forest harvest has the largest overall effect (if one normalizes by precipitation) during dry years and that effect diminishes as precipitation increases. The question then becomes, does that 100 mm increase result in a significant increase in pore pressures during a really wet year.

Key Review Questions:

4a. The execution of the project and the report follow the original proposal and the revisions to the scope. The only exception is that the author compares ET over forest to ET over shrub. The original scope calls for an estimate of ET over grassland. However, the reviewer feels that ET over shrub is a more appropriate.

4b. The design and the execution of the project are not consistent with accepted scientific methodology. As discussed above, the author introduces an unsupported parameter to allow her model to simulation data at one site correctly, and subsequently is unsure as to the form of the model to proceed with. A more correct approach would be to explore the limitations of the forcing data set and perform the experiment with an unaltered form of the PM equation.

4c. The model parameters, in general, were appropriately assigned, with the major exception of EWP, which is an unnecessary parameter justified based on a limited calibration to a single site.

4d. Conclusions are consistent with results, given the limitations discussed above.

4e. Methods are not consistent with future application. By introducing a weakly justified parameter that must be calibrated to specific site data, the GAETQ model, which the author seems to adopt as her benchmark model, can not be easily applied to different locations with forest cover and can not at all be applied to sites of different vegetation cover.

4f. No.

4g. The question of winter evaporation differences between a forest and shrub is an important question. The author has done a thorough job in describing the literature available on this subject. While the model formulation is not unique (with the exception of the weakly justified EWP parameter), the application and questions addressed are.

Additional Review Questions:

Model Structure: The model structure should be revised to exclude the EWP parameter.

Meteorological Inference: The meteorological inference procedures are not sound. It is not appropriate to simply assume that precipitation at SeaTac doubles but not consider the effect that this increase would have on the RH. The reviewer believes that the limitations of the SeaTac data forced the author to adopt the EWP parameter. The model should instead be rewritten to exclude the EWP parameter and then should be tested directly on the Vancouver Island data.

Implementation assumptions. See above under Meteorological Inference.

Parameters seem sound.

5a. EWP is weakly justified and strongly influential. Details are given above.

5b. All conclusions are uncertain due to the EWP parameter. The results from the simulations where EWP is not used (GAETP model) are also uncertain because the author never presents a plausible series of simulations using GAETP to match the Vancouver Island data.

5c. Yes, nearly all results will change if EWP is removed and the GAETP model is correctly applied.

5d. Uncertainty is addressed adequately, given the limitations of the model formulation. Unfortunately, it is the EWP parameter that introduces the largest uncertainty of all, namely, which form of the model to use for different types of vegetation.

5e. Yes, if the model is made more general, it could be used in the context of a distributed hydrology model to identify hillsides which may be prone to failure.

Comments:

Section 1.4: Does the author have a reference to support the statement that shortwave is not variable between years.

Section 1.8.3. Conclusion 1. Interception loss sensitivity is limited to albedo. This may be simply an artifact of the author's choice to force RH to be 100 during winter months. By effectively forcing the Vapor Pressure Deficit term of the PM equation to zero, albedo is the only parameter left that can control evaporation from the canopy.

Section 1.8.3. Conclusion 6. It is not correct to say that RH shows no influence on winter AET, this was an a priori assumption. While the author admits so in this section, it is more clear to state "Since RH was set to zero (one?) during winter, it is not possible to determine the influence of winter RH or winter wind speed on winter AET."

Section 1.9.2. Source of Uncertainty #3. The uncertainty regarding model formulation is not simply due to a question on the importance of vertical advection. The entire hypothesis that RH should be set to 100 percent during winter is the largest source of uncertainty.

Section 1.9.2 Point 4. While I agree with the statement that shrub ET during winter is unlikely to exceed ET from a forest canopy, it is exactly the degree to which shrub ET should be expected to be less than from a forest that is the central question here. And as the author admits, the uncertainty over model formulation cast significant doubt on the results and the conclusions that can be drawn from them regarding this expected difference.

Section 1.10.2. Specific Recommendations, Points 4 and 5. By using the Vancouver RH values directly, the author can and should attempt to address these questions directly.

Page 25. Regarding TMY2 data. See comment above under Major Concerns. The author should not use an "average" year to simulation something that occurs during extremely wet years.

Table 2.1 Lnet column (39.3 versus –39.3) Is this a typo?

Figure 2.1. Not clear in my copy. I assume a good fit was achieved. Please identify which if any of these periods include rainfall. I assume calendar days 311 to 317 since Qstar is low.

Page 28. If the attempt is to model the first decade after harvest, which includes conifer sapling growth, is a 1m height too small?

Page 28. Canopy gap fraction. Exactly what is it. In reality it never gets to 100 percent even for a mature forest. Typical values are 80 to 90 percent.

Figure 2.2 How is energy flux density calculated, energy flux includes latent heat. Was this calculated at SeaTac, or does the plot show net radiation? Why does one of the curves start at 20 (Is this the accumulated energy flux). This figure is confusing. Also it is not correct to refer to the dates in Figure 2.2 as being w.r.t. water year. April 1 is not the start of the water year.

Section 2.6.1. Validation. By employing the EWP parameter, the author has forced the PM to match the Vancouver island observations. I don't present detailed comments on this section much of the analysis, results and conclusions in this section need to be redone without the EWP parameter.

Table 2.7. The author reports estimated annual forest evaporation using the PM equation with measured RH values of over 1500 mm per year. These results are far too high and reveal a fundamental flow in either the underlying met data, the model formulation, or the model parameters. My guess would be a combination of the met data and the model parameters. The reviewer has used the PM equation, together with explicit canopy interception models for a large number of applications (using measured RH); annual predicted ET's over forest seldom exceed 800 mm (close to the authors no advection case).

Table 2.9. Is it reasonable to allow advection in the GAETQ model (bottom right portion of the table). Since GAETQ effectively parameterizes advection, isn't this akin to counting advection twice.

Page 40. The lower bound for annual AET is presented as 188 mm, however this is based on the GAETP formulation – and therefore should not be compared to the forest results, which are based on the GAETQ formulation. Therefore the actual "apples to apples" comparison suggest a range for shrub of 361 to 492 mm

Page 41. Soil Moisture Patterns. Due to the two different formulations of models and the three advection cases (none, strong, moderate), this section is terribly confusing. It is not clear which line corresponds to exactly which type of simulation. Furthermore, these results really do need to presented for a "wet" year during which landslides should be expected to occur.

Figure 2.8 Typo in legend "in in".

Section 2.8 Discussion. The author attributes the unrealistic result obtained for the "strong advection case" to the fact that RH at SeaTac is much lower than would be expected over a vegetated surface. This is 100 percent true and should have ruled out SeaTac as a valid station with which to do this analysis. The author also admits that at least one author 'showed that the PM equation is able to correctly simulate the actual latent heat fluxes from a wet canopy . . . provided that good (met data) is available." This once again point to the strong need to formulate this report and the entire analysis around the Vancouver Island data. (not SeaTac). Once again, the uncertainty regarding model formulation must be removed before any conclusions can be drawn from this report.

Page 48. "The GAETQ latent heat flux results for forest compare favorably to observation made above a 50 year-old Douglas-fir stand on Vancouver Island. Except for (total net radiation) being much lower, the climate there is similar to that of the Puget Sound Lowland.". This may be true, but the climate of Vancouver Island is not similar to SeaTac airport, which is the source of many of the problems in this report.

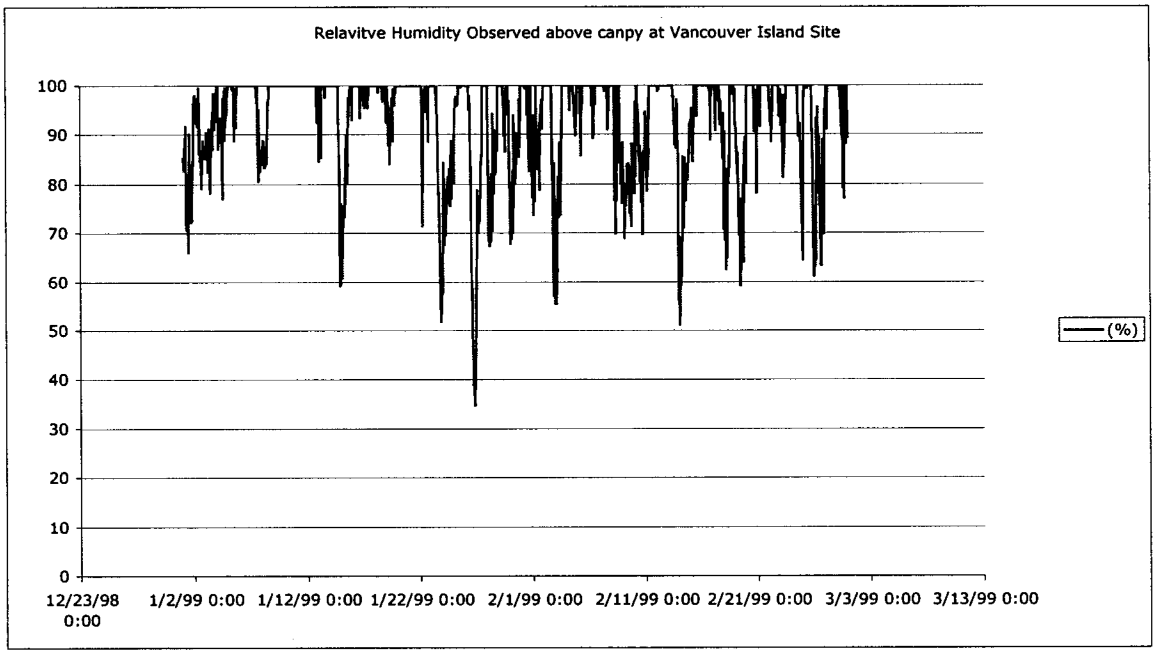

Figure 1. Observations of RH above a mature forest stand on Vancouver Island. The authors assumption that RH = 100% during the entire winter is not justified

Reviewer B

Review of

"Estimation of a multi-season evapotranspiration within humid temperate forest lands in relation to vegetation cover. I. Analytical assessment and model description"

Key Review Questions

a. Is the design and execution of the project consistent with the original proposal and subsequent revisions to the scope of work?

To answer this I will address each of the proposal objectives.

Part I, a) Present and defend an a priori parameterization of the Penman-Monteith equation for application to continuous multi-year simulations (at sub-daily time-step) of vegetated-mediated moisture flux over forested and cleared lands in a temperate humid climate;

The study presents a detailed description of the model and its application to the problem of vegetation conversion. A defense of the model is attempted but it is questionable whether this defense is successful. This is something that is acknowledged in the report in terms of the number of questions unanswered and assumptions that still require justification, and also through the recommendations for future research, which propose to address these issues.

However, if the proposal objective is taken literally, then the model was not actually applied over multiple years but was only applied for a single year using a climatological forcing dataset. In addition an evergreen shrub cover is used to represent the cleared land simulation. Although some evidence is given that the evergreen shrub cover is more typical of the years subsequent to clear-cutting, no evidence is given that such a cover approximates the first winter of clear-cutting, and it is stated that this first winter is more likely to be deciduous cover. The model is indeed applied to a temperate humid climate.

Part 1, b) Present model results for at least two NOAA (hourly-reporting) meteorological stations in western Washington.

Model results are presented for simulations forced by the TMY2 hourly meteorological data from SeaTac airport. The TMY2 data are derived from NOAA NWS Surface Airways datasets. Assuming that NOAA in the proposal refers to NWS Surface Airways data then the model is applied to NOAA data (albeit for a derived dataset) but for only one station. The study states that in Washington (not just western Washington) there are 9 of these SA stations but only the SeaTac dataset has all the variables required by the model.

As the original task list of part II was replaced by the revised task list I will only comment on the revised list.

Part II, 1) Use WRCCF (Wind River Canopy Crane Facility) data [contains short wave and long wave data] set to develop regressions for estimating components of the energy budget from short wave radiation.

Section 2.2.1 and 2.2.2 describe the use of the WRCCF data to develop such regressions. Only the data from autumn of 1999 and 2000 were used as this is purported to resemble the Puget Sound Lowland climate. It is of concern that data from the autumn is applied to the wintertime regime in Puget Sound and especially to the summer season. Also, the results indicate good agreement for all components in terms of their average fluxes and a reasonably low mean absolute error. It is expected that K_{out} could be predicted quite accurately as it is just equivalent to $(1-\alpha)K_{in}$. K_{in} is taken as the measured value and the albedo is also given. It may be that the good fit is obtained because the albedo was not in fact measured at the experimental site but was estimated from the above equation as part of analysis of the experimental study. In the development of the regressions, the energy storage terms (e.g. ground heat flux, canopy storage) are ignored. It is not clear whether this is a valid assumption for this climate and vegetative cover. I give some examples of studies that show that these terms should not be ignored later in this review.

Part II, 2) Run the model with the SeaTac airport hourly data [contains short wave data and cloud cover information; represents grassland].

The model was run with the SeaTac airport hourly data, albeit using the TMY2 derived dataset. This is therefore consistent with the project objective.

Part II, 2a) Quantify the uncertainty in the model predicted energy budget contrast for forest vs. grassland, and how this translates into uncertainty in the contrast of radiative-forced AET and groundwater profiles.

Taking this objective literally, the study does not compare forest with grassland, but forest with evergreen shrub. Although the difference between grassland and shrub may be small, the study does not explicitly address this issue and so the study is not consistent with the original proposal objective. If we ignore this difference and look at what the study actually addressed, i.e. the contrast between forest and shrub, the study is consistent with the original proposal. Section 1.6.1 summarizes the method used to quantify the uncertainties in the model results. The use of high and low parameter values for each vegetation cover leads to an uncertainty range in the simulated energy budget and AET values. This translates into uncertainty in the groundwater profiles through the differing recharge inputs and the use of a range of values for root zone moisture capacity and aquifer transmissivity. The final overlap of the uncertainty bounds between the two vegetative covers gives an indication of the significance of the change. The study presents results that are consistent with this objective. Section 1.8.2 summarizes the uncertainty range for forest and shrub and the range in the conversion between the two vegetation types. It also describes the uncertainty in the change in groundwater storage. Sections 2.7.1 and 2.7.2 describe these uncertainty ranges in detail.

Part II, 2b) Quantify the uncertainty in the energy budget magnitude when the only available data is daily precipitation, maximum and minimum air temperature (as at NCDC station).

Sections 1.6.3, 1.8.4 and 3 describe methods for disaggregating daily meteorological variables to hourly time step and the effects of this, in comparison to using the original hourly data, on the simulated energy budget. The disaggregation method assumes that precipitation is uniformly distributed over the day, the diurnal cycle of air temperature is modeled by a sine wave function using the daily maximum and minimum temperature as anchor points and hourly net short wave radiation is estimated as a function of extraterrestrial short wave radiation, albedo and precipitation. However, net long wave radiation is not estimated. This estimate of short wave radiation was validated using the Wind River dataset for autumn of 1999 and 2000 and showed a good fit to the measured data. As the parameters of the equation for estimating short wave radiation are essentially calibrated to fit the available data, the uncertainty in using daily data on the short wave energy components cannot be ascertained.

These estimates were used to run the model in advection free mode with forest parameters for the TMY2 dataset for a number of experiments using various combinations of original hourly data and disaggregated daily data. These experiments showed that the effect of using daily temperature and short wave radiation on the latent heat flux is negligible. However the winter latent heat flux is sensitive to the use of daily precipitation. The study does not explicitly quantify the uncertainty or error in using daily data; rather it just describes the general effects. These data are obviously available from the simulations carried out but they are not presented in the study report. The issue is complicated by the use of the EWP calibration variable, which is simply adjusted to compensate for any detrimental effects of using an incorrect diurnal precipitation distribution.

b. Is the design and execution of the project consistent with accepted scientific methodology?

In general, the project is carried out in a manner consistent with accepted scientific methods. This can be summarized as follows: the development of model appropriate to the application, construction of forcing datasets with which to test the model and run simulations, sensitivity testing of the model to variations in key parameters, validation against observed data, modification of model in response to sensitivity testing and the validation results, use of the final model for prediction of the consequences of change and finally assessment and discussion of the results with recommendations for future research directions and model developments. However, the details of these activities reveal a number of deviations from accepted methods and the use of methods that are inconsistent with the data/application or which may give results that are misleading. Specific examples are given next.

- The use of the TMY2 forcing dataset has a number of features that could be considered to be inconsistent with accepted scientific methods. Firstly, the TMY2 dataset is supposed to represent a typical year of climatology for the station in question. However, it appears that it consists of individual months taken from specific years (Section 2.2.1), e.g. January from 1988 and February from 1966. This does not necessarily represent a typical year as each month is taken from a specific year. These years may indeed be typical for the month in question but this is not apparent.

- The supposed advantage of using only 1 year of data is completely at odds with scientific methodology. It is stated that this has the advantage that it simplifies the processing of data. This is no justification when we take into consideration the benefits of obtaining information about the effects of inter-annual variability and extreme events on the simulated water budget through the use of multiple years of forcing data (if available).
- As the dataset does not contain precipitation, this must be obtained from a concurrent NCDC dataset; it is unclear as to the location of the NCDC station and whether the precipitation at the NCDC is consistent with the TMY2 data. For example, a wet day will generally have lower incident radiation because of increased cloud cover. In addition, the precipitation record was doubled in winter to make it more typical of the Cascade foothills. This was done without modifying radiation because of the purported invariance of radiation at annual time scales. This may be true, but this is not relevant to the question of whether radiation should also be adjusted for the Cascade foothills location. As the absolute values of radiation components will likely also be different for this location they should be scaled accordingly. This argument may also apply to the temperature record, which could be scaled with the elevation lapse rate.
- The method of validation cannot be regarded as based on sound scientific methods. Firstly, the comparison is an indirect validation. Although this is acknowledged in Section 1.6.2 it provides little useful information on the performance of the model for the following reasons.

  The use of the ratio of AET to available radiation cannot be regarded as a robust validation index because it is based on the unjustified assumptions that this experimental finding is transferable from the study site at which it was observed.

  The use of precipitation and meteorology forcings from a different site is likely to produce a different response to that at the validation site. The validation results (Section 2.6.1) are given only for forest. It appears that lack of data prevented validation for the clear-cut vegetation case, but this leaves the validity of the model in doubt. For the forest validation, only the forest HIGH parameters were used. Why was the LOW parameter set not used as well? If there is uncertainty in the parameter values how can one set be chosen over another? Would it not be better to carry out the validation with both sets of parameters to see if the range of results envelops the observations? This would give more confidence in the results and the model.

  In the end, the results of the validation show that the model does poorly in simulating the observed behavior at the Campbell River site, except for summer AET, which may be a coincidence. This is not surprising given that the model is forced with data that are not from the Campbell River site and so is unlikely to produce similar flux data. It should be noted that the Ameriflux network (http://public.ornl.gov/ameriflux) now has datasets for this site (forested and clear-cut) with data gaps infilled thus providing continuous sub-daily meteorology and flux measurements.
- To simulate the results better, the model was altered so that the winter AET matches the available radiant energy (Section 2.6.1). This change was applied in winter only and this seems to be done so that the better fit to the observed summer

AET is retained. This could be considered to be weak scientific methodology in that the model is basically being calibrated on a seasonal and sub-seasonal basis (as in the case of the 2 values for EWP in winter). As such, the model could be made to fit any dataset without necessarily simulating the physical processes correctly and being able to partition the water budget in a reasonable manner. Assuming that the use of the Campbell River data for validation is justifiable, then the results using the modified/calibrated version of the model (Table 2.5 and 2.6) can only be useful if they can do a reasonable job in reflecting the seven observations given in Section 2.4. The calibration effort, by design, ensures that the ratio of winter AET to available energy is near unity. However, the observed fraction of AET that occurs at night time (50% for winter and 10% for summer) is only approximately attained in the calibrated simulation (41% for winter and 0% for summer). The observed during-storm interception loss is 22% of winter AET but it is 41% for the model simulation. Observed winter transpiration is about 30% of total winter AET but the simulation results is about 19% (TR = 46, AET = 246). Furthermore, the good fit to the summer AET value is lessened. One could say that these are fairly reasonable results, but just as easily say the opposite.

- The framework for the assessment of the effect of vegetation conversion is generally in line with common methods. The use of uncertainty bounds is a documented method for estimating the changes in a system given uncertainty in parameter values (e.g. Beven and Binley (1992)). However, it should be noted that the results that are very wide make the predictions essentially unusable. This study makes some effort to assign typical values on some of the parameters but uses values obtained from measurement studies for other parameters. Even these measurements should have uncertainty attached to them. This is especially the case if they are derived from measurements from another site, such as is the case for the albedo values taken from the Wind River dataset. Care should be taken to ensure that key sensitive parameters are allocated reasonable ranges of values that reflect the uncertainty in their values given information in the literature and observational datasets.
- The setup for the simulations used in the final assessment of the effect of vegetation conversion is somewhat questionable because the model is implemented inconsistently, with one version of the model used for three of the simulations and the other version used for the shrub LOW simulation. This makes it impossible to compare these simulations in terms of the effects of ranges of the parameter values, as the model version used is different for one of the simulations.

c. ***Were the model parameters and their values appropriately assigned? If not, what parameters and values should have been used?***

The canopy height value was set at 40m for forest and 1m for shrub. These values seem reasonable in light of the results of the sensitivity test and the results for a 40m canopy and a 1m canopy shown in Table 2.7, which indicate that the model is fairly insensitive to this parameter. Albedo values of 0.08 (winter) and 0.11 (summer) were chosen for forest and 0.1-0.2 (winter and summer) for shrub. A number of reports give ranges of values that are slightly wider than these. For example, 0.05 to 0.15 from Oke

(1987) and 0.10-0.15 from Pielke and Avissar (1990) for evergreen forest. The values for shrub appear to be reasonable but should there be such a large difference between winter and summer values?. LAI values of 6.0 – 8.0 were chosen for forest and 2.0 – 4.0 for shrub, which seem to be reasonable. The Global Leaf Area Index Dataset of Scurlock et al. (2001) indicates values with a mean of 5.47, standard deviation of 3.37 and maximum values of 15.0 for coniferous forest. The mean value for shrub is given as 2.08, standard deviation of 1.58 and maximum value of 4.5. These do not seem to be at odds with the values used in this project.

The ranges for canopy storage (1.0 – 3.0 mm for forest and 0.5 – 1.0 for shrub) and the threshold insolation for stomatal opening (50 - 70 W/m**2 for forest and 35 - 70 for shrub) are appropriate. The root zone storage capacity was set to 250-350mm and 150-250 for forest and shrub respectively. These values should depend on the rooting depth of the vegetation cover and the soil type in terms of porosity, wilting point and field capacity. Typical rooting depth values from the global study of rooting depths by Schenk and Jackson (2002) indicate values of about 2.5m for temperate forest. When combined with typical fractional available water content (field capacity minus wilting point) of between 25 and 45% this results in root zone storage of between 625 and 1125mm. If the model is being applied in a non site-specific manner then this simple calculation indicates that the range of values in this study may be too low to capture the possible uncertainty in its value.

There are also a number of non-parameter settings that should be evaluated as well. These include the vegetation type that represents the clear-cut vegetation. It may be useful to simulate the situation for deciduous vegetation as suggested in Section 2.3 as slope stability could be most vulnerable immediately after clear cutting.

d. Are conclusions consistent with results?

- *Winter ET is a non-negligible for evergreen needle-leaf forest and may be significant also for non-forest vegetation.*

  The evidence for this appears to come from experimental data (the validation data) and from the model results, although this is not explicitly stated in the results. However, finding an answer to this is a recommendation in the Key Recommendations section of the Executive Summary that indicates that this result was not actually shown in this study. The author acknowledges that there is little or no empirical data in Section 1.1 substantiating this claim and only refers to the preceding study of Sias (1977) as evidence. However this earlier study requires peer review (the purpose of this review) and validation against empirical data and as yet this has not been done. Therefore this conclusion is somewhat in doubt unless accompanied by the words potential or possible. Only one observational dataset is given in evidence, the Vancouver Island dataset and this indicates that winter AET is 7% of winter precipitation and about 6% of annual precipitation (Table 2.3). This could actually be considered an insignificant part of the annual budget. More evidence is required to substantiate this conclusion or it should be revised to state that it is a possibility. In addition, no discussion is given about the situation for non-forest vegetation cover although the conclusion supposes that AET may also be significant in winter.

- *The model results do not rule out the possibility that forest to shrub conversion could have little or no hydrologic effect.*

  Basically what this is saying is that the results are inconclusive and as such may be used to show that there is little or no effect due to conversion. This appears to be true as the lower range for the change in AET from Table 1A is 3mm, indicating essentially no change. This is also reflected in the change in groundwater storage from Figures 1.3 and 1.4, which show that the change in groundwater storage is essentially zero for low values of aquifer transmissivity. In addition, it should be noted that these figures only shows the case of conversion using the forest HIGH parameters and the shrub LOW parameters that have the largest difference in simulated AET. The results using the forest LOW and shrub HIGH parameters would likely show little difference in groundwater storage for any value of transmissivity. This is because the change in AET is small and the resulting change in recharge would also be small. It appears therefore that this conclusion is consistent with the results.
- *The model results indicate that significant hydrologic effects could result from forest to shrub conversion, and that these effects are likely to be in a direction that is unfavorable for slope stability, and, conversely, unlikely to be in a direction that favors increased slop stability.*

  The upper limit on the range of the change in AET (forest HIGH to shrub LOW) from Table 1A is –333mm (no advection) or –432mm (moderate summer advection). The resulting changes in groundwater storage are not given in quantative terms but Figures 1.3 and 1.4 (2.6 and 2.7) indicate that this can be over 100mm for the majority of the wet season for low values of aquifer transmissivity. These values can indeed be considered to be significant changes of the total water budget given annual precipitation of 1420 mm for these simulations. If the link between pore pressure and slope stability were substantiated then the results would be consistent with this conclusion.
- *The major sources of uncertainty in the evapotranspiration simulations are 1) lack of knowledge as to which version of the model to use in the case of shrub and 2) lack of knowledge as to what value to assign to the calibration parameter (EWP) in the modified model (i.e., GAETQ).*

  It is unclear as to why the second version of the model was applied only to the shrub LOW and only in winter in the conversion simulations. In any case the uncertainty in which version of the model to use is irrelevant until the model is properly validated. Furthermore, the choice of the value of the calibration parameter seems obvious if it is required to ensure that the simulation matches the observed data.
- *The major sources of uncertainty in the groundwater storage simulations are the following: 1) Already-stated uncertainties in the evapotranspiration simulations, 2) uncertainty about the change in the timing of the start of the groundwater recharge season, and 3) uncertainty about what value to assign to the parameter that defines the rate at which the water table falls (and groundwater is discharged) during periods of no-recharge.*

  The uncertainty about the timing of the start of the recharge season seems to be governed by the root zone moisture capacity and the value of aquifer transmissivity and is not necessarily a direct source of uncertainty. This conclusion should be modified to state that there is uncertainty in the value of root zone moisture capacity.

- *Although some questions remain to be answered, test results show good feasibility for using data from daily-reporting NCDC stations to run both models.*

  This conclusion is consistent with the results as presented, although the details of the results of the test simulations are not given. It may be useful to present these details so that the level of sensitivity is quantified. The simulations could also be done with data from more than one NCDC station so that the range of response is obtained. It may be that the chosen station experiences a certain type of weather such that it is sensitive to the diurnal cycle of precipitation. Another station may respond very differently if it is subjected to different storm types. Also, winter AET is sensitive to the diurnal cycle of precipitation which manifests itself in changes to transpiration and interception of opposite sign. It would be useful to know whether the net change is significant or whether the changes in transpiration and interception cancel each other out and result in a zero net change. If the latter is the case then the effect of the diurnal cycle of precipitation on the seasonal water budget is irrelevant.

- *Research to address the major sources of uncertainty and to determine appropriate procedures for calibration of GAETQ is necessary if this model is to be used as a screening tool. To avoid calibration, it will likely be necessary to have at-site measurements of near surface relative humidity and windspeed, or to couple the hydrologic model to a multi-layered atmospheric boundary layer model.*

  Addressing the major sources of uncertainty is indeed vital if this model is to be used in a predictive fashion. The wide ranges of results obtained from the different versions of the model and different parameter values makes the model somewhat unusable in its current un-validated form to be of practical use in this respect. Therefore, the results do indicate that further research is required to reduce the uncertainties.

e. Are methods and results consistent with scope of work and future applications?

The basic scope of the project is to investigate the possible range of changes in AET and groundwater conditions as a result of timber harvest and assess whether the methods can be used to form the basis of a site assessment tool. The answer to this can be found by looking at what was actually done in the project and what results were obtained. The model was applied to a single site for two vegetative covers and the resultant changes in AET and groundwater storage were calculated. This is consistent with the scope of the work as defined above. Determining whether the project was able to provide the basis of a site specific assessment tool depends on the extent to which site data can be obtained. In terms of meteorological forcings, the use of the NCDC stations, which are relatively numerous in Washington State, was demonstrated as a viable surrogate for the lack of widespread hourly data. However, issues related to the applicability of such station data to landslide susceptible sites that are not necessarily in close vicinity have still to be addressed. In addition, there is great uncertainty in assigning values to groundwater parameters and characteristics for a specific site.

f. Is any information missing that is necessary to evaluate the results of the project?

The paper uses a number of assumptions that are critical to how the forcing datasets are developed, how the model is applied and the analysis of the results. Some of these assumptions are based on previous studies but the project does not reference these studies in this report. It would be useful to see these studies cited so that the results can be evaluated better. For example, section 1.8.1 refers to studies that show interception loss rates of less than 20 percent but does not cite them. Section 2.7.1 states that *"ample evidence that AET of well-watered crops and wet forest in the growing season obtains Q*"* but this evidence is not shown.

A number of summary results are given and conclusions made without showing the quantitative results. There is no way to evaluate or check these results without the availability of the data in the form of tabulated values or figures. For example, the results of the comparison of simulations forced by hourly and daily data, and the sensitivity tests, which only indicate the qualitative influence of the parameters on the model but does not give any quantative details.

g. Is this original work? Is there similar or parallel work that is not cited?

This study appears to be original work. It attempts to quantify the effects of vegetation conversion on wintertime evapotranspiration and the resulting effects on groundwater recharge and storage for the climate of lowlands of the Cascades with a view to analyzing the risk of deep-seated landslides. A search of the literature reveals no other studies that have looked at this specific area. There are a number of similar studies that have addressed some of these issues but they have been treated separately or/and are for different regions. For example, there are a number of studies that have looked at the link between logging and slope stability at different location in North America (Croft and Adams, 1950; Bishop and Stevens, 1964; O'Loughlin, C. 1974; Gary and Megahan, 1981, Matthias, 2000). Similar studies that are specific to the Northwest US have concentrated on western Oregon (Swanson and Dryness, 1975; Swanson and Swanston, 1977; Miles et al., 1984; Miles and Swanson, 1986; Weaver and Hagans, 1996). There have also been a number of studies on the effect of clear-cutting on runoff hydrology in the western Cascades of Oregon (Jones and Grant, 1996; Thomas and Megahan, 1998; Beschta, 2000; Jones, 2000). Much of the literature on the causes of landslides appears to concentrate on the effect of root structure (Wu et al., 1979; Ziemer, 1981). However the only studies looking at the link between landslides and evapotranspiration seem to be Sias (1997) and Miller and Sias (1998).

Additional Review Questions

Model features:

- Model structures (section A.3)
- Meteorological inference procedures (sections A.4, 2.2.2)
- Implementation assumptions (section 1.3.2)
- Parameter values (Table 2.2 in section 2.3, Table 1.1? Perhaps this should be Table 1.2?)

a. ***Are any of the listed model features both (a) weakly justified and (b) strongly influential with respect to significant results? (Examples?)***

In general, the answer to this question is yes. There are a number of features of the model and their implementation that fall into this category. I give a number of examples of this below. It should be noted that the study does acknowledge the majority of these weaknesses and offers some ideas for overcoming any deficiencies.

- Aerodynamic conductance is calculated using the Jarvis model, which equates it to the product of drag coefficient and wind speed. The drag coefficient is a function of vegetation of canopy height, screen height and roughness lengths. Some of the assumptions used in these formulations are based on closed forest canopies only, which may be problematic for the application of the model to the shrub vegetation cover.
- Soil moisture accounting uses a single state variable for root zone moisture content. Change in water content is calculated from a simple water balance relating infiltration, transpiration, and groundwater recharge. The overall scheme for handling the states and fluxes of moisture in the subsurface may be a major limiting factor in the accuracy of the model and thus may be highly influential on the results presented. Firstly infiltration is formulated as a constant fraction of precipitation rate and is actually set to a constant value of one for the simulations. This is likely to be unrepresentative of physical reality for most situations as infiltration rate is a function of not only precipitation rate but also of soil moisture conditions This situation is exacerbated when coupled to a single root zone moisture bucket such that there is no vertical distribution of soil moisture and root density. The major influence of these factors on infiltration and evapotranspiration is therefore not allowed for in the model. Despite these deficiencies, the introduction of a more rigorous model of subsurface moisture dynamics is a potentially intensive activity and this must be weighed against the increased confidence gained in model performance.
- Is direct evaporation from the soil a significant part of the water budget? In the case of clear-cutting it is likely that vegetative cover becomes minimal in the first year (and to some extent in the next few years) such that transpiration would reduce considerably but would see increases in soil evaporation.
- The methods for setting the initial conditions for the root zone and groundwater in Section 1.4 are unclear. The initial root zone water content is set to capacity and this is purported to ensure that the end of year value is also at capacity. It is unclear why this should be the case and further explanation is required. To ensure that the initial and final groundwater storage values match the initial storage was

adjusted for each value of transmissivity. It is unclear why the two states have to match. Furthermore, the "calibration" of the initial value for each value of transmissivity makes the inter-comparison of simulations impossible as any differences between simulations may be due to the effects of differences in the initial conditions.

- The assumption that energy balance storage terms are negligible is justified in section A.4.2 through the use of experimental findings from a previous study for forested plots. This study found that they could be ignored over seasonal time scales. It would be useful if these studies could be cited so that this assumption can be assessed. There are studies that have shown that soil heat flux is non-negligible. For example, Ogée et al. (2001) showed that soil heat flux was significant at hourly and monthly time scales for forested sites. In the case of canopy heat storage, many studies have ignored its contribution, which appears to be valid for vegetation with low height and LAI but not for dense forest (Stewart & Thom, 1973, McCaughey, 1985; McCaughey & Saxton, 1988).
- The canopy surface resistance regression equations for Douglas fir area applied in this study to forests and those for salal are applied to shrub. The regression equations, which are based on summer-time measurements, are assumed to apply in winter also. Section A.3.4 and A.3.5 describe the regression equations and their range of applicability. It appears that the equations are weakly justified for certain ranges of soil water tension as shown by low correlation values. Furthermore, the validity of transferring these equations to a shrub vegetation cover and for winter conditions is not addressed in the study and so the justification for using these equations is not known.
- The assumption that infiltration capacity always exceeds the precipitation rate and that therefore surface runoff never occurs could be problematic. Surface runoff is neglected in the model implementation and it is unclear from this study whether this is a valid assumption. Given that the soil is saturated for the majority of the winter (from model simulations and observations) it is likely in reality that surface runoff will be generated from saturation excess and possibly from infiltration excess. In the clear-cut case this situation could be exacerbated because of the reduced interception and greater throughfall to the soil surface. The model specifically uses a constant infiltration fraction equal to one, which means that all water reaching the ground infiltrates. In reality the infiltration rate is a function of precipitation rate, soil type, soil moisture content, etc. Therefore, it is reasonable to expect that part of the uncertainty in the model and its results is attributable to ignoring these processes.
- Recharge rate is calculated as infiltration in excess of root zone storage and this excess moisture is routed instantaneously to the groundwater system. It is unlikely that the moisture profile in the root zone is such that recharge only occurs when the root zone is saturated. However, in the climate under consideration, the consistently wet winters may result in near saturated conditions throughout the season and thus this model may be a reasonable approximation of reality.
- The assumption that the D-B aquifer is isolated from the adjacent groundwater system is weakly justified in a real world application at a particular site because of the potentially large differences in the groundwater regime that may be expected

at different sites. In the case of this study, however, the implementation of the model is not site specific and as such the influence of the regional groundwater system cannot be accounted for.

- EWP is a calibration parameter that was introduced to help reproduce the assumed influence of vertical advection. Firstly, this is weakly justified because as it is based on the assumption that vertical advection is a significant process in forest canopies and possibly in low vegetation as well. Secondly, it assumes that the GAETQ version of the model can simulate vertical advection although the report acknowledges that this is a simple way of achieving this. Finally, it is assumed that the calibration parameter EWP can be set so that winter AET matches available energy, another assumption that is only justified for one experimental site. The influence of EWP on AET, and thus on the significant results of this study, is high.
- The root zone water content is highly influential on the groundwater results as it governs the onset of recharge. No information is given about the source of the range of parameter values chosen so it is difficult to ascertain whether these values are justifiable.

*b. **Should any of the results or conclusions be considered more uncertain than described in the report because of a weakly justified model feature?***

- The premise that winter AET is a significant part of the water budget is uncertain given that it is based on the results of Sias (1997) and the model described in this report. The model of Sias had not been submitted to peer review and is known to have weaknesses. Although this study tries to address some of the weaknesses of the original model of Sias, the model described in this report is weakly validated and is implemented in an idealized manner in terms of meteorological forcings and soil and groundwater characteristics. Therefore, this premise must be viewed with some skepticism, especially given the finding of previous studies.

*c. **Would the simulated effect of forest harvest on wet season groundwater dynamics have been different if a particular model feature had been treated in a more defensible manner?***

- None of the model implementation assumptions can be considered to have an influence on the results if they were treated more defensibly. This is because they all taken as fixed assumptions with no attachment of uncertainty to their justification.
- The choice of the version of the model, GAETP or GAETQ, is known to have a relatively large affect on the model results. The justification for using one version or the other is weak because of the unknown influence of vertical advection and its significance for different sites and vegetation covers and the lack of validation data to test and give confidence in the models.

*d. **Are all of the major sources of uncertainty identified and adequately addressed?***

A number of major uncertainties are identified in the study, some of which are addressed. The study also makes some recommendations to address the remainder of the identified uncertainties. There are also a number of uncertainties that are not identified in the study.

- The major uncertainty related to vertical advection is which version of the model to use (i.e. GAETP or GAETQ) and what value to assign the EWP calibration parameter. This really is a question of whether vertical advection occurs over both vegetation types, as the version of the model with the EWP parameter was developed to simulate vertical advection.
- The uncertainties in the vegetation parameter values are dealt with by using uncertainty intervals in their values. This is a valid way of handling this uncertainty but can also lead to unusable predictions if the range of results is relatively wide. A number of the fixed vegetation parameters could conceivably be given uncertainty intervals, such as the gap factor, which may vary widely between vegetation types, and especially immediately after clear-cutting. An increase in this parameter would increase direct precipitation to the ground and thus increased available water for root zone infiltration and recharge.
- There are also identified uncertainties related to the groundwater regime, namely, the predicted timing of the start of recharge and the value to assign the aquifer transmissivity. It appears that the major governing factor on the timing of the start of recharge is the root zone moisture capacity such that recharge only occurs when the root zone is at maximum moisture capacity. The root zone capacity is vegetation dependent and the uncertainty in its value is represented by a minimum and maximum possible value. However, it is unclear whether the given range does actually represent the uncertainty in its value as discussed before.
- The range of values for the transmissivity is between 3 and 180 days, which results in a wide range in the simulated groundwater storage profiles. The transmissivity is a function of aquifer breadth and hydraulic conductivity and is very site specific. This uncertainty and the necessary assumptions about the local groundwater regime mean that the model is forced to be an idealistic representation. Although the study identifies the uncertainties in these parameters as playing a central role in determining the potential effects on slope stability, it does not address these uncertainties, which is not surprising given the difficulty of the problem.

There are a number of uncertainties that are not identified and therefore not addressed. Most of these are related to the simplifying assumptions used in the model and how it is implemented.

- See the discussion about surface runoff given above.
- Another source of uncertainty is the role of direct evaporation from the soil surface, which is not a process that is addressed in the model. Soil evaporation could be a major component of summer and even winter total evaporation. The opening up of the canopy as a result of clear cutting could enhance the potential contribution of soil evaporation.
- The simulations shown in this study are forced with an idealized forcing dataset, which is supposed to represent the climate in the region. By using this forcing dataset the uncertainty that would be introduced via the interannual variability and the occurence of extreme events is ignored. The fact that the interannual

variability is not taken into account is acknowledged in the study but the author fails to acknowledge the potential importance of this in giving a range of response. At one extreme, a year with negligible precipitation would show little difference between vegetation types as no water would enter the soil and groundwater and thus the water table would be governed solely by the aquifer characteristics. At the other extreme, a year with very high precipitation would saturate the soil for longer periods of time and elevate the water table regardless of the vegetation cover. Although these are extreme and highly unlikely scenarios, the point is that the prevailing meteorological inputs are the driving force of the land surface water budget and so variations in their quantity should be taken into account when assessing the effect of vegetation changes.

- The importance of a particular parameter to the uncertainty in the results depends on the actual uncertainty in the parameter value and the sensitivity of the model to the parameter value. The sensitivity of the model to a parameter can be quantified as the ratio of the change in the result to the change in the parameter value. When variation in other parameters is also included there is uncertainty about their combined interaction as the effect may be non-linear. For example, the assumption that parameters, which individually yield high AET, will in combination also yield the highest AET is not certain. It is possible that simulations that use combinations of intermediate values of the parameters may result in more extreme values of AET. The combined effect of multiple parameters can be seen by simultaneously changing the values of the parameters by selecting a set of values for each parameter and running the model for all combinations of parameter values. As an alternative to using parameter sets that consist of the upper and lower bounds, as in this study, a statistical approach, such as Monte Carlo analysis, could be used to reveal the any non-linear effects.

e. Do the model results indicate that further research on this topic would lead to a method for identifying deep-seated landslides that could be destabilized by timber harvest?

It appears that the model and methods described in this study could provide a sound basis for the investigation of the potential for deep-seated landslides under vegetation conversion, but this would entail considerable effort in terms of future research to attain a useable model. Namely, the model would require a more thorough evaluation, through testing, calibration and validation, using a range of forcings and validation data. This is problematic because of the apparent lack of data relevant to the location and of the intended application. If data do not become available, there is however, potentially a great deal to be learnt from applying the model to other locations and datasets which will likely reveal weaknesses and strengths of the model and provide indicators for model modification and tuning. Only once the model is verified and validated would confidence be instilled in its predictions for the Puget Sound region and the conversion from forest to clear-cut. The study makes a number of recommendations for future research that will improve the likelihood that the model will be useful as an assessment tool for the risk of landslides.

If the link between elevated groundwater storage and slope stability is true, then the methods presented in this study could be the only way to estimate the potential changes in recharge and groundwater storage. However, the estimates that this method would provide would have to be accompanied by some estimate of the uncertainties in the predictions, as it is likely that the site-specific nature of the processes involved would make it difficult to provide a definitive answer.

Specific Comments

- The ordering of the sections and the section headings are inconsistent between Section 1 "Overview and Summary" and the other sections (notably Section 2). This makes it very confusing when trying to relate the different sections.
- Paragraph 4, sentence 3 of the Executive summary should be "Deforestation may lead to *a decrease* in evapotranspiration..."
- The methods for setting the initial conditions for the root zone and groundwater in Section 1.4 are unclear. The initial root zone water content is set to capacity and this is purported to ensure that the end of year value is also at capacity. It is unclear why this should be the case and further explanation is required.
- References should be cited for the performance of the P-M model in section 1.4.
- Would it be plausible that the low vegetated cover in the first year after clear-cutting (as described in section 1.5) produces the most extreme changes in evapotranspiration and resulting groundwater storage and therefore the worst case scenario for the risk of landslide? If this were so, then would it not be useful to model this scenario as well?
- Did the sensitivity analysis described in section 1.8.3 use a number of different parameter values within the ranges given? Or did it just use the maximum and minimum values given? It is possible that combining intermediate values of parameters may result in more extreme results.
- Section 1.9 refers to the three questions that the project is intended to answer (as listed in the goals of section 1.2). However, section 1.9.1 states that the project was intended to address four fundamental questions. It is somewhat confusing, without the original project proposal/contract, to understand what is meant here.
- To ensure that the initial and final groundwater storage values match the initial storage was adjusted for each value of transmissivity. It is unclear why the two states have to match. Furthermore, the "calibration" of the initial value for each value of transmissivity makes the inter-comparison of different simulations impossible as they were not initialized the same.
- The intended result that the initial and final groundwater storage values are equal is not shown in the results in Figure 1.3.
- No account is taken of the vertical distribution of transpiration as governed by root profiles. The use of multiple layers and rooting profiles may provide a more accurate picture of the relevant processes, although this adds considerable complexity to the model.
- The annual values for the forest LOW simulation in Table 1-1-B are inconsistent with the seasonal values for the same simulation. This may be a typographichic error.
- There are possibly a number of typographic errors in Table 2.1. The footnotes b and c should be interchanged. The value of modeled L_{net} should be –39.3 and not 39.3. The values of Q* calculated from these mean values should be 64.3 for the measured case and 63.6 for the modeled case. Should the equation indicated by footnote (d) be $L_{in} = L_{net} + \sigma T^4$ as $L_{out} \approx \sigma T^4$ and $L_{net} = L_{in} - L_{out}$?
- Paragraph 2 of section 1.6.2 makes statements about the similarity of fluxes over different vegetation types but does not give any explanations. As this relates to important issues about the validation process should these not be stated here?

- Section 1.8.5 compares the results of this study with the results of Sias (1997). The validity of comparing these two datasets is in doubt because of the major differences between the models, parameter values and model implementation.

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Reviewer C

Review of "Estimation of multi-season evapotranspiration in relation to vegetation cover from regions with rainy-winter/dry-summer climate" prepared by Joan Sias

Prepared for the Committee for Cooperative Monitoring Evaluation and Research, Scientific Review Committee

1.0 General:
This report describes the initial step in development of a management tool for identification of zones where forest harvest may promote failure of deep-seated landslides. It describes a model for estimating evapotranspiration from different land cover types and estimation of the meteorological inputs necessary to drive the model. I believe that the approach presented represents a valid technique for assessing water balance changes in response to vegetation change. In it's current form, however, the model contains some poorly-justified assumptions and inadequate validation for use as a general management tool. I address the review questions posed by the Scientific Review Committee below, followed by a section detailing my specific comments and concerns. Finally, I provide a list of minor editorial comments and typographical errors.

2.0 Key Review Questions (from Section 4, Background Materials: Sias 2002)

a. Is the design and execution of the project consistent with the original proposal and subsequent revisions to the scope of work?

The work summarized in this report is consistent with the original proposal and amendments, as summarized in Section 1. However, the task list for Part I requests model results for two hourly-reporting meteorological stations in western Washington, while only results for the SeaTac airport station were presented.

b. Is...the project consistent with accepted scientific methodology?

The general approach of the project is consistent with accepted scientific methodology. I question some aspects of the actual model design, as described in Sections 3.0 and 4.0, below.

c. Were the model parameters...properly assigned?

In my opinion, canopy height, albedo and leaf area index are all assigned reasonable values. They do not represent absolute minimum and maximum values, but rather a range within regularly occurring values. I am confused by the description of the insolation threshold for stomatal opening and cuticular resistance, as described in comments 16 and 22 in Section 4.0. Root zone storage capacity is extremely site specific and it is difficult to assign average values. I think values double those listed would be perfectly acceptable.

d. Are conclusions consistent with results?

The conclusions are consistent with the results presented in the report.

e. Are methods and results consistent with...future applications?

I have noted a few areas where I think the current methods may be insufficient for future applications of a regional model for prediction of groundwater recharge sensitivity to vegetation change. Each of these is described in Section 4.0:

- Need for spatial heterogeneity in groundwater recharge (comment 3);
- Need for multi-year simulations (comment 17);
- Need for parameter values for additional vegetation types (comment 2); and

- Need for transferability of radiation relationships (comments 13 and 19).

f. Is any information missing that is necessary to evaluate the results of the project?

Some aspects of the report are unclear, such as how longwave radiation was calculated and used (comments 9, 13 and 14 below) and how the threshold for stomatal closure was used (comments 16 and 22), which make it difficult to evaluate why the original model predictions were higher than expected. In my opinion, the subsequent model "fixes" (advection-free mode and the introduction of GAETQ) only serve to obscure this original problem. In addition, there is insufficient validation presented to assess how well the model is performing (see comment 8).

g. Is this original work? Is there similar or parallel work that is not cited?

I do not know of any other modeling work being done specifically to look at the occurrence of deep-seated landslides. However, the review of existing literature in this report is very limited (probably intentionally), so there is a great deal of related work, including previous efforts to observe and simulate hydrological effects of land use change, that are not cited (see comment 1 below).

3.0 Additional Review Questions (from Section 5, Background Materials: Sias 2002)

Assess the following model features with respect to the questions that follow:

- Model structures (Section A.3);
- Meteorological inference procedures (Sections A.4, 2.2.2) – addressed in comments 4 and 13;
- Implementation assumptions (Section 1.3.2) – addressed in comments 2 and 3; and
- Parameter values (Tables 1.1, 2.2) – addressed in comments 16 and 22.

My assessment of the latter three model features can be found in Section 4.0, as noted above.

With regard to model structures, there are two features that are both weakly justified and strongly influential with respect to results, these are the assumption of 100% humidity ("advection-free mode") and the calibration of winter potential evaporation ("GAETQ").

In my experience, it is not accepted methodology to set relative humidity to 100% in the absence of horizontal advection. In fact, in most situations it is assumed that horizontal advection is negligible (i.e. that surface conditions are uniform over an adequate upstream fetch) which is how we can assume that a meteorological station set up at one location in a field is approximately representative of the wider region. While it is true that in a sealed system, water vapor input to the air via surface evaporation will eventually saturate the air column, leading to 100% humidity, to assume that this is always the case neglects the effects of molecular and turbulent diffusion in the atmosphere.

Fixing relative humidity to 100% in these simulations helps to create the need for the second model adaptation. With the "advection-free" assumption, the second term of the P-M equation becomes zero, so AET/Q* cannot exceed $\Delta/\Delta+\gamma(1+\pi)$. The GAETQ model increases AET, but does it all through interception evaporation, rather than transpiration, which leads to twice as much interception evaporation as observed, as shown in Table 2-6.

Both of these model features are the results of trying to tune the model results to fit one particular set of observations, and may mask an underlying problem with the original model which led to the original over-prediction of evapotranspiration. I think that all of the results should be considered uncertain, because the physical basis of the model has been removed, and even so the model has not been shown to reproduce all aspects of the "validation" dataset.

How large an effect this will have on the predicted groundwater dynamics is still unknown. As the preliminary model results suggest, any change in winter ET is small relative to the total precipitation inputs to the system being modeled. I believe that future research on this topic may lead to a method to identify destabilization of deep-seated landslides. However, at this point the largest sources of uncertainty still lie in the formulation of the model itself.

4.0 Specific comments and concerns:

1. Section 1.1, 2nd paragraph: The author minimizes the level of information that can be obtained from previously conducted field studies regarding the effects of vegetation change on water balance throughout the Pacific Northwest. Although direct studies of evaporation from intercepted rainfall alone may be limited, there are numerous paired catchment studies and plot scale work that may be useful.

2. Section 1.3.2. Assumption 4: The text overstates the generality of the model. Given that vegetation parameters are based on only two vegetation types, both in the case of the Wind River dataset used to determine LAI, canopy height and albedo, and in the Tan et al. dataset used to determine stomatal conductance, there is no basis for generalizing to "all forest" and "all shrub". The results should be stated in terms of Douglas Fir and Salal. If future use requires application of the model to other vegetation types, other input parameters must be identified.

3. Section 1.3.2. Assumption 9: Ultimately, evaluation of the risk of deep-seated landslides will require taking into account the effect of regional topography in concentrating ground water flow at the land slide location. The proposed water table profile takes into account the increase in water table depth with distance from the divide (assuming the entire contributing area underwent the same vegetation change), but it neglects the influence of any groundwater flow that may be entering the site laterally, such as in the case of a convergent hillside or hollow.

4. Section 1.4, 1st paragraph. While I agree that precipitation at Darrington, WA should be greater than at SeaTac, no reasoning is provided for why double precipitation is valid. Reference to surrounding precipitation stations or a regional map of annual precipitation, such as the PRISM product produced by the University of Oregon would be appropriate. In addition, I do not understand the justification for not altering the other meteorologic variables. Why would the interannual variability of radiative inputs influence their spatial variability, when cloud cover in the foothills is likely greater than at SeaTac? Why is the variation in air temperature with elevation neglected? The resulting vapor pressure deficit calculated at Darrington would be smaller if air temperature was lapsed from SeaTac and may account in part for the overprediction of ET by the original model.

5. Section 1.4, 2nd paragraph. For clarification, the first sentence should state that the root zone moisture content is set equal to field capacity. While in this model the total soil moisture storage is truncated at field capacity, usually total capacity is greater than field capacity and this statement can be misleading.

6. Section 1.4, 2nd paragraph and Section 2-5, 2nd paragraph. While for this model, soil moisture storage is likely to be at the same "maximum" value of field capacity on April 1st of each year, in reality, actual soil moisture storage may vary widely between field capacity and complete saturation on April 1st depending on the time since the last rain event. It is more conventional in the Pacific Northwest to choose a water year that begins at the end of the summer dry period, where the absolute magnitude of the interannual variability is soil moisture storage will be smallest.

7. Section 1.5, 1st paragraph. As stated above, the text throughout should refer to Douglas Fir and Salal rather than forest and shrub since all vegetation parameters were essentially derived for these two vegetation types only.

8. Section 1.6.2, 3rd paragraph and Section 2.4, 1st paragraph. Using SeaTac data to try to reproduce evaporation fluxes measured on Vancouver Island is truly an indirect validation. Could met data from the Vancouver Island research site be used to drive the model (or at least from the Victoria or Vancouver airports)? Could the Wind River Canopy data be used to validate model predictions of latent heat, if only for a few weeks at time? In addition, comparison of AET/Q* is maybe appropriate as a general comparison, but ultimately prediction of the quantity of AET is what is important for the prediction of slope stability. Even if AET/Q* is reproduced correctly, errors in the estimation of Q* may lead to large errors in the predicted quantity of AET. In my opinion, the validation presented in this report to date is not adequate to demonstrate if the model can be transferred to other locations to give reliable evaporation predictions without on-site calibration. Such transferability is essential, unless the model is only intended for application at detailed field sites, where a full suite of observed variables are available.

9. Section 1.6.3, last paragraph. It is not entirely clear when longwave radiation was used and when it was neglected. According to this section, longwave radiation was neglected when using the NCDC data, was it neglected in the other cases? If yes, this is a major assumption that is not clearly presented, and has important implications for the interpretation of model performance, in particular the problems with nighttime evaporation.

10. Section 1.8.1, general. The first bullet indicates that winter evapo*transpiration* was 80% of precipitation, while the 3rd paragraph indicates that the interception loss rate was 80% of precipitation. Shouldn't interception loss just refer to the evaporation from wet vegetation, not transpiration of the vegetation itself?

11. Section 1.9.2, 1st bullet. The author must be cautious of estimating winter ET via a basin water balance that neglects changes in subsurface storage. For an annual water balance it is fairly standard to neglect changes in subsurface storage, but this becomes much more difficult when trying to isolate the winter period alone.

12. Section 1.9.2, 5th bullet. The primary question is appropriate values of over-canopy relative humidity. The question of horizontal advection is secondary.

13. Section 2.2.2, equation 2-2. I don't see the advantage to original regression equations to estimate longwave radiation rather than a more conventional approach using a straight application of plank's law with an adjustment for cloud cover/atmospheric transmissivity that can be derived from the observed dataset (e.g. based on the ratio of clear sky to observed radiation). The wind river dataset can be used for validation, in order to select appropriate values of emmissivity.

14. Section 2.2.2, equation 2-2 and Table 2-1. Footnote c (should be d) to Table 2-1 indicates that Lin = σT_s^4. When combined with equation 2-2b, this indicates that Lout = $\sigma(1.15T_a^4 - 2T_s^4)$-95, while the text indicate that outgoing longwave is calculated at canopy surface temperature. Section 2.3 indicates that Lout = σT_a^4. Difficult to evaluate what was used with all of the contradictions. It appears that equation 2-2 is unnecessarily complex and I expect that the estimation of longwave radiation could be very influential in the accurate prediction of nighttime latent heat. In addition, why is there no MAE for Lout in Table 2-1? Based on the numbers provided, there is a sign error for modeled Lnet. How is MAE for Lnet so high, when the measured and modeled are identical?

15. Section 2.6.1, Table 2-4. This is the first mention of E_{eq}, and the definition is not clear from the footnote alone (it wasn't until I saw the definition for α_{eq} in Appendix B that I understood what this column represented).

16. Section 2.7.1, 2nd paragraph. $r_s x$ should be defined in the text. I am surprised that $r_s x$ is the most influential parameter controlling summer transpiration, it makes me wonder whether Qsm and Tm are set to cause stomatal closure too frequently.

17. Section 2.7.2, general. Multi-year simulations will be needed to encompass a range of extreme events, as well as different temporal patterns of storm sequence in order to identify the risk of slope instability. I agree that the model results are correct in showing that in the Pacific Northwest, with extremely wet winters, the change in winter recharge to ground water in response to forest harvest will be minor relative to the summer effect. The question then is whether the change in summer recharge is persistent enough to create a new equilibrium in ground water levels. This makes it essential to pin down τ_{90} and perform multi-year simulations.

18. Section 3.2 and Table A-1. Stomatal conductance depends on vapor pressure deficit...is this set to zero in the advection-free runs, leading to a constant value of stomatal conductance, or are the SeaTac RH values used?

19. Section 3.2 and 3.3. The text indicates that the calculated values of atmospheric transmittance ($\sum K_{in}/\sum K_{ex}$) are not transferable (i.e. the values for Wind River were different than for SeaTac). Therefore, rather than presenting these as a pre-determined constant in equation 3-1, it would be better to show this as a site-specific variable.

20. Section 3.4. Since I think the use of EWP should be discarded, it will also be necessary to propose a new method of determining the diurnal distribution of precipitation, such as sampling from the nearest hourly station, either on an hour-by-hour or statistical basis.

21. Section A.2, 3rd paragraph. The earlier text (i.e. Section 1) is somewhat misleading in declaring that the model allows no water to leave the system laterally as surface or shallow subsurface runoff. In this section we find that the model can allow this, however for this application the parameter INF is set to zero.

22. Section A.3.4, 2nd paragraph. The text states that $Q_s m$ and Tm are the minimum values of radiation and temperature required for stomatal opening to occur, but the first sentence implies that they are the maximum values for which stomata are open, or the minimum values for stomatal *closing* to occur, since r_{st} is set equal to the canopy resistance for closed stomata when $Q_s m$ and Tm are exceeded. The values assigned to $R_{st}x$ appear consistent with the latter definition, i.e. they correspond to a maximum resistance value, appropriate for closed stomata. However, $Q_s m$ and Tm appear consistent with the first definition. These values are very low, and I would expect stomata to be open at radiation levels greater than 50-70 W/m^2 (see Comment 16).

23. Section A.3.4, equation A-12. With the coefficients listed in Table A-2, it is not possible for $\Psi_s(t)$ to take on negative values, yet all of the values in Table A-1 are negative.

5.0 Typographical errors and editorial comments:

1. Executive Summary, 3rd paragraph. Deforestation may lead to a decrease in evapotranspiration, not an increase.
2. Executive Summary, 4th paragraph. Extra word "the" in 4th sentence.

3. Acknowledgements. Spelling of "individuals" in 2nd sentence.
4. Acknowledgements. Spelling of "led" in 4th sentence.
5. Section 1, general. There are no page numbers in Section 1.
6. Section 1.1, 3rd paragraph. Extra word "groundwater" in last sentence.
7. Section 1.3, 3rd paragraph. The third bullet should read: "the Dupuit-Boussinesq (D-B) baseflow equations for a horizontal, isotropic, and homogeneous aquifer *with* fully penetrating stream."
8. Section 1.6.2, 1st paragraph. I think that net precipitation should be precipitation less predicted evaporation, not evapotranspiration.
9. Section 1.6.2, 3rd paragraph. In the third sentence: "The model was run in advection-free *mode*..."
10. Section 1.6.2, 3rd paragraph, and throughout document. Relative humidity should be considered a percent unless otherwise stated, therefore a relative humidity of 1.0 is misleading.
11. Section 1.6.3, last paragraph. I have noted some inconsistencies between variable symbols in the text and those listed in Appendix B. For example, Kex is not listed in Appendix B. Available radiation Q*, is listed in Appendix B, but in Section 1.6.3 and equation A-31, net radiation is called Q(t). Are these the same?
12. Section 1.8.1, last paragraph. Spacing problem in the first sentence.
13. Section 1.8.3, last bullet. RH_{bs} is not in Appendix B and is not defined in the text.
14. Table 1-1. The annual total in the Forest LOW_ET column of Section B is added incorrectly.
15. Section 2.0. "Equation" should be plural in the 10th sentence.
16. Section 2.1, 1st paragraph. Incorrect grammar in the last sentence.
17. Section 2.2.1, 4th paragraph. The first sentence should read: "Data...*were* used...".
18. Section 2.2.1, 4th paragraph. "Area" appears twice in the 4th sentence.
19. Section 2.2.2, 1st paragraph. The phrase "have units of" appears twice in the 2nd sentence.
20. Section 2.5, 1st paragraph. The first sentence should read "...*the* Puget Sound Lowland".
21. Section 2.5, 1st paragraph. The second sentence should read "*The* latter site...".
22. Figure 2-2. The units should be labeled on the axes of Figure 2-2.
23. Section 2.5, last paragraph. The fifth sentence should read: "Root zone storage is equal to *field* capacity...".
24. Section 2.6.2, 5th paragraph. The second sentence should read: "...in *the* model."
25. Section 2.6.2, 5th paragraph. For clarification, I think the third sentence should read: "...the algorithms *for stomatal conductance* for summer were applied to winter."
26. Section 2.7.1, 1st paragraph. Error in the last sentence.
27. Section 2.7.1, 2nd paragraph. "uncertainty" is misspelled in the last sentence.
28. Section 2.7.2, last paragraph. The first sentence should read: "When advection is allowed to occur, GWS decrease*s*..."

29. Section 2.7.2, last paragraph. The word "then" is not needed in the second sentence. Figure 11 does not exist in this section
30. Section 2.7.2, last paragraph. "amount" is misspelled in the last sentence.
31. Section 2.7.2, Figure 2-8. In the figure caption, "in" is repeated and "each" is misspelled.
32. Section 2.9, 1st paragraph. The 2nd numbered point should read: "Rather than treating it as *a* vegetation parameter…"
33. Section 2.9, 4th paragraph. "positive" is misspelled in the third sentence.
34. Section A.1, third paragraph. In the 5th sentence, "behavior" is misspelled.
35. Section A.3.2, fourth paragraph. The 1st sentence should read: "…the typical results are z_{om}=0.1 H_c…"
36. Section A.3.6, 2nd paragraph. Error in the last sentence: "Cx is the effective depth *of* stored on a canopy…"
37. Section A.4.1, 2nd paragraph. In the 3rd sentence, the difference in net radiation between what two covers was small? The text is unclear on what was being compared.
38. Section A.5.1, 1st paragraph. The word "is" should be deleted in the 5th sentence.
39. Section A.5.1, 2nd paragraph. The word "that" is repeated in the second sentence.

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June 26, 2003

Professor Daniel Vogt
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Dear Dan:

RE: "Estimation of multi-season evapotranspiration in relation to vegetation cover from regions with rainy-winter/dry-summer climate" by Joan Sias

Enclosed are three reviews of this report. It is clear from the reviews that each of the reviewers read the report carefully. There is no point in reproducing the specifics of the reviews here, but there are some major points that demand particular attention. Although the review form does not ask for specific recommendations, my interpretation of all three reviews is that the equivalent of "major revisions" in the terminology used by most journals will be required before this report can be useful to the client.

Reviewer A states, "… the work suffers from a major flaw …". As detailed by the reviewer, the perceived flaw is the introduction of a parameter (EWP) that facilitates a match of simulated and observed evapotranspiration. The reviewer argues that the problem is much more likely traceable to the use of meteorological data from Seattle-Tacoma airport, which is at least 100 km distant from the field site. Also, the author has prescribed relative humidity throughout the winter season as 100%, which is a demonstrably inaccurate assumption. There are now methods that allow transfer of meteorological data based on local conditions, and furthermore, it is almost certain that there are data records at or near the field site that could be used. Perhaps even a few years ago the difficulties in accessing climate data justified use of remote index sites, but this is no longer the case. Various data sets now exist that provide the forcings required to run land surface models. Among others is the Land Data Assimilation System (LDAS) project, which provides surface forcing data over most of North America. Another data set has been assembled by Peter Thornton (now at NCAR), which is applicable over most or all of the western U.S. I am inclined to agree with the reviewer that modifying the Penman-Monteith equation, which has been widely tested and applied globally, with an arbitrary factor is not defensible.

Reviewer B addresses each of the review questions posed quite literally. Some of the points raised are not major issues in my estimation – for instance, comparison of forest with evergreen shrub rather than grassland is, I believe, quite justifiable. However, other points are more substantive, for instance the comments that the report's conclusion that winter ET is non-negligible for evergreen needle-leaf forest is not well substantiated. The 1997 report is not peer-reviewed, and can hardly be used as a justification. The issue of winter ET has major implications for CMER, and in fact directly or indirectly was the motivation for the study, this issue needs to be resolved. Given the criticism of the modeling approach by the reviewers, it does not appear that a credible argument can at present be based on the model results. The reviewer's comments on model features deserve careful attention as well. Apparently the soil moisture accounting scheme is a very crude one, by the standards of modern land surface models. It's hard to understand why the author did not start with an accepted land surface scheme, of which many are around (see for instance various reports of PILPS – Project for Intercomparison of Land-Surface Parameterization Schemes). To me, it would have made far more sense to start with a credible land surface scheme, and then focus on its evapotranspiration algorithm, with particular focus to evergreen temperate forests. It is worth noting that many of these models user some variation of the Penman-Monteith algorithm.

Reviewer C states, "In its current form, however, the model contains some poorly-justified assumptions and inadequate validation for use as a general management tool". The main technical points questioned by the reviewer are the assumption of 100% relative humidity in winter (noted also by Reviewer A) and the calibration via an arbitrary adjustment factor of potential evapotranspiration (also noted by the other reviewers). The reviewer feels, and I concur, that these assumptions may well have resulted from attempts to tune the model to a specific data set (which is not necessarily representative of the field observations), and may have masked more fundamental problems with the model.

Overall, the reviewers have gone through the report very carefully, and have uncovered what I believe are some fundamental deficiencies. At this point, it is not clear how best to proceed. If this were a journal submission, my recommendation probably would be "reject with encouragement for resubmission". It is clear from the reviews that the results are not presently usable in a management context. On the other hand, the work may provide the basis for improved management in the future – but only with considerably more analysis, which I am assuming is not funded under the contract that supported this work. As indicated above, I do question the need to develop a model specific to the PNW, as there has been a good bit of hydrologic modeling work done that should be applicable, and would in any event serve as a better starting point.

Sincerely

Dennis P. Lettenmaier
Associate Editor
Professor of Civil and Environmental Engineering

C.3 Author's Response

C.3.1.1 Author's response to SRC reviewers' comments and cover letter (1/21/04).

The individual reviews contain many positive comments, including in response to questions about the originality of the work, and whether further research in this vein could lead to a method for identifying DSL's that could be destabilized by timber harvest. There is mostly agreement as to what are the major weakness of this work. Direct validation (**DV**) of GAETP with the Campbell River (**CR**) data is strongly recommended by all three reviewers. I think the report will be greatly improved by DV, as to do so will address most of the criticisms of the reviewers (**A,B,C**) and the referee (**D**). What follows is an itemized list the major criticisms, followed with a brief response. I first list the major concerns itemized by D. For each statement, I indicate which reveiwer(s) held the concern.

1.D writes "As detailed by the reviewer [A], the perceived [major] flaw is the introduction of a parameter (EWP) that facilitates a match of simulated and observed evapotranspiration.... [M]odifying the Penman-Monteith equation...with an arbitrary factor is not defensible**."(ABCD)** This criticism can be adequately addressed through DV of *both* versions of the model. Even though the reviewers were highly critical of parameterizing the advection term (i.e., replacing it with EWP in the "Q" version of the model), I continue to have a strong opinion that there is much value in directly testing whether this idea is viable. My reasons for this opinion are given in **Comment 1**.

2. I set relative humidity (**RH**) to 100 percent for the GAETP indirect validation (Table 2-4, Table 2-6). **(ABCD)** In hindsight, I agree that this assumption is not defensible. DV will eliminate this problem. By way of further explanation, I was working from the premise that the RH data at Seatac corresponds to horizontal advection, which in theory should be absent at CR. In fact, vapor pressure deficit can be caused by horizontal *or* vertical advection, and therefore will not necessarily be zero when a site is placed so as to minimize horizontal advection. Running GAETP in advection-free mode caused GAETP to underpredicted AET. Unfortunately, I didn't realize the error in my rationale until I received these reviews. This is the underprediction problem with GAETP alluded to by D and Reviewer C. Had I run GAETP with Seatac RH for purpose of indirect validation, I would have greatly overpredicted ET in the indirect validation (Table 2-7). This is the overprediction problem with GAETP alluded to by D and A. The under/over-prediction problem thus is not due to any structural flaw in the model.

3.Using data (Seatac) that is 100 km distant from the "field site" (Darrington), rather than using up-to-date methods for transfer of meteorologic data and/or using data sets such as mentioned (i.e., LDAS; Peter Thornton's data set). **(ABCD).** I don't think this criticism is very appropriate, since Darrington was not a field site per se, and because I required detailed meteorological data for this project, both for forcing the Penman-Monteith (**P-M**) equation, as well as for the aggregation/dissagregation study. A person looking for a weather station in or near the Cascade foothills of Puget Lowland that provides most or all of the forcing data elements at the required temporal resolution will not find a nearer station than those at Seatac or Olympia airports. It was beyond the scope of my project to assimilate a complete data set from daily NCDC data or some other source. Furthermore, based on my experience with and knowledge of the P-M equation, I doubt that lapsing the air temperature would have much effect on the model output for a snow-free location. The main problem with using Seatac data is RH, not the temperature data (**see Comment 2**). In any case, RH is highly sensitive to surface conditions, including vegetation type and dynamic wetness status.

I strongly doubt that the data sets mentioned by the referee (LDAS, Thornton) provide RH data that can be safely assumed to be representative of near-surface conditions over forestland (**see Comment 3**). Such data is only available from micrometeorologic data sets, of which Ameriflux sites (e.g., Campbell River, B.C.; Wind River, Washington) are the best examples. In any case, these data sets will not solve the problem of estimating how the meteorological variables would change for an alternative surface cover.

4. I agree that the results of this report do not provide strong evidence that ET is a <u>substantial component</u> of the winter and annual water budget for forest in the winter-wet/summer dry climate **(B)**, and that the conclusion to this effect must be omitted or modified, or else supported with empirical data (**see Comment 4**). One reviewer recommends adding the word 'potentially' to this statement. I think this is appropriate, since there is some (albeight limited) empirical evidence (i.e., Stewart, 1977; Humphreys et al, 1999; Mizutani, 2000) showing that a known physical mechanism (i.e., vertical advection during storms produced by wet frontal weather systems) can support significant direct evaporation rates during rainfall. I must point out that I did not use Sias (1997) to support this statement.

5. <u>The soil moisture accounting scheme (SMAS) is "very crude"</u> **(D).** I agree, but it is fairly unlikely that replacing the SMAS with a more sophisticated one will have substantial effect on cumulative winter transpiration. Because summer transpiration cannot in principle exceed the sum of summer precipitation plus plant-available water capacity plus capillary upflux, it is difficult to conceive how a sophisticated land surface scheme is going to have a substantial effect on summer transpiration. It is possible that the the timing of the onset of the groundwater recharge season could show significant sensitivity to the SMAS. Considering that the groundwater simulations are highly idealized to begin with, and the many uncertainties therein, I don't think that using a crude SMAS significantly weakens the value of the groundwater simulation effort. (B says simplistic groundwater recharge assumptions may be justified for wet winter climate.) In any case, it is not warranted to invest much effort in modeling groundwater effects before (a) we know with empirical confidence that ET effects are significant, and (b) we have a demonstratably valid above-ground water vapor flux model for pre- and post-harvest states.

6. D concurs with Reviewer C's "feeling" that my use of GAETQ "<u>may have masked a more fundamental problem with the model</u> **(CD).** No specific reason is given, so it is difficult to respond to this comment. Apart from D's criticism of the SMAS, none of the reviewers (including C) offered any major criticism to the model description given in Appendix A. It is conceivable that there is a significant coding error. I doubt this, however, since I went to great lengths to detect and eliminate such errors. Direct validation would help to put this question to rest.

7. D writes <u>"The main technical points questioned by the reviewer [C] are [a] the assumption of 100% relative humidity (also noted by Reviewer A) and [b] the calibration via an abritrary</u>

adjustment factor of potential evapotranspiration (also noted by the other reviewers)." For a response to [a] see item 2 above. For a response to [b] see item 1 above.

8. D writes "I do question the need to develop a model specific the the PNW." This is a general model, as it is based on the P-M equation and the Rutter interception (**RI**) model. The choice of parameter values and forcing data determines whether an application of the model is pertinent specifically to the PNW.

9. D writes that there is other hydrologic modelling work that "would in any event serve as a better starting point." D is probably referring to applications of DHSVM (Wigmosta et al., 1994). Since D did not give specific reasons for this opinion, I can't offer a rebuttal, except to give some of the reasons I chose not to use DHSVM in the first place. (1) I desired a point application of PM+RI model. As DHSVM is a distributed model, I suspected it might be cumbersome to implement as a point-model. (2) In my work I am focusing on ET simulation, not streamflow simulation. Generally, the encoding of DSHVM is oriented toward calibration and validation of streamflow predictions, and especially peak flow predictions, and I don't believe that a good match of model and observed streamflow is a strong test of the validity of a Penman-Monteith application. (3) If I had started with DHSVM, I would need to modify a code I am not familiar with in order to implement deviations from DSHVM structure and to obtain the detailed output I required. To make changes to a complex and unfamilar code could be far more time-consuming than starting from scratch. At the very least, having independent P-M based codes (e.g., GAET and DHSVM) is scientifically desirable because of the rich opportunities for cross-verification and testing sensitivity of output to structural and parametric differences of independent codes.

10. B and C have suggested revisions to some of the parameter values. I will follow these suggestions in any follow-up work. B critizes use of TMY2 data; Performing DV would eliminate use of TMY2. The reviewers disagree on the thoroughness of the literature review.

11. There are a variety of comments/concerns/recommendations given by the reviewers, which I don't think are significant enough to list for purpose of this initial response to the reviews. I am cataloging all of these, and expect that catalogue should be useful if UPSAG decides to have me revise the report.

Comments.

1. I continue to believe that the use of EWP was not unjustified for the indirect validation, since the RH data at Seatac was wholly inappropriate to a forestland simulation. In my opinion the indirect validation results of GAETQ (i.e., the EWP parameterization of advection) were surprisingly good considering that I did not calibrate EWP to optimize any of the results except for forcing seasonal AET to match seasonal cum. net radiation. I suspect that because RH data of sufficient quality is only available from long term micrometeorological studies (which are few in number), the use of P-M for management purposes will require a parameterizaton of the advection term, perhaps along the lines I used for GAETQ. Of course, any parameterization scheme will need to be validated and demonstrated to be transferable. Alternatively, it may be necessary to evaluate management questions through sensitivity testing, wherein the advective contribution to winter AET is treated as a sensitivity variable, e.g., with RH set on the basis of

educated (empirically-informed) guesses as to what cumulative winter AET should be over a given vegetation in a given locale.

2. Recently published research proves that P-M predictions are quite sensitive to whether RH is measured or estimated (Waichler and Wigmosta, 2003). The authors tested five methods for estimating RH. Of these, only one method (i.e., their method 4a) required no at-site RH or dewpoint temperature data for calibration or input. Method 4a in effect assumes *specific* humidity is constant throughout each 24-hour period, and sets it equal to the saturation vapor pressure calculated at daily Tmin. Their results with method 4a are most relevent here, because this is the data situation one will most often be faced with in routine applications of the P-M equation. The authors find that annual ET (and also flood magnitude) predictions are severely degraded when estimated RH (i.e., estimated by method 4a) is used in place of measured RH. Reference: S. Waichler and M. Wigmosta, (2003). Development of hourly meteorological values from daily data and significance to hydrological modeling at H.J. Andrews Experimental Forest. Journal of Hydrometeorology. April 2003. pp. 251-263.

3. I have perused the LDAS web-site. It appears that RH data provided by LDAS would consist of estimates, rather than measurements, and that these estimates would be based on daily Tmin and Tmax, using a method similar to what Waichler and Wigmosta (2003) have now shown gives poor results in the P-M calculation (i.e, their method 4a and simulation "P3"). As for Peter Thornton's data set, the only humidity variable is daily average vapor pressure (P. Thornton, pers. commun.). Again, from Waichler and Wigmosta's results we can infer that the prospects for obtaining a good method for estimating hourly RH from Thornton's data are poor. Neither data set will solve the problem of estimating the effect of alternate vegations covers on humidity.

4. Waichler et al. (2002) have compiled data from H.J. Andrews interception, and sap flux studies that show winter annual ET is ~742 mm. The Oct-March flux is 265 mm, which is, coincidentally, quite close to what I arbitrarily assumed for the GAETQ application to Puget-Sound Lowlands foothills Cascades. Scott R. Waichler, Mar, S. Wigmosta, and Beverley C. Wemple, Nov. 2002. Simulation of water balance and forest treatment effects at the H.J. Andrews Experimentant Forest. Pacific Northwest National Laboratory. Technical Report No. PNWD-3180. This research has been submitted to Water Resources Research.

C.3.1.2 Author's Comments

1. What have we learned form this report and for which there is significant scientific certainty, i.e. that SRC could agree to, e.g. conclusions, uncertainties.

Major conclusions and sources of uncertainty are listed in the Executive Summary and in Section 1.9. The reviewers have suggested that I incorporated the word 'potentially' in the first conclusion, where I state "Winter evapotranspiration is a non-negligible component of the annual water balance..." I agree that this change is necessary and significant, and have incorporated it. Apart from this, the reviewers have not indicated any disagreement with my major conclusions. Nevertheless, I have modified the list of conclusions in the Executive Summary slightly, in order to emphasize the importance of uncertainty in relative humidity data.

I think it is constructive to offer here a more general answer to this question than is provided in the Executive Summary.

1. It seems to me to be a widely held opinion that, in winter, evaporation occurs at significant rates only during rainfree intervals, and is driven mainly in winter by radiant energy. In this report I have emphasized that there does exist a physical mechanism that can support significant rates of during and between-storm evaporation, at rates in excess of the available radiant energy, even though vapor pressure deficit may be quite small. I believe that the reviewers of this report would strongly agree with the assertion that vertical advection must be taken into account in any effort to understand hydrologic effects of timber harvest in our climate.

2. I believe the reviewers would agree to the following.

a. Because of vertical advection, it is *possible* that cumulative winter evaporation for needle-leaf forest can, in principle, exceed by a substantial amount, the cumulative available radiant energy.

b. There is a physical rationale to support a hypothesis that vertical advection-forcing of evaporation is weaker or absent over non-forest or (dormant) deciduous forest vegetation. (In my literature review, I have not yet found definitive empirical proof for this hypothesis.)

3. The literature review and the analysis in this report indicate that relative humidity and precipitation are critical meteorological forcing variables for wet season latent heat flux. In particular, it appears that these variables need to be available or reasonably well estimated at a sub-daily temporal resolution (e.g., 3-hour or better). Applications of the screening tool will rarely have the needed data. Any further effort to develop a screening tool will have to address the lack of quality at-site relative humidity and precipitation data.

4. Two variables appear to be critical for determining the effect of potential changes in ET and recharge on the seasonal progression and magnitude (peak value) of groundwater table elevation. These are aquifer hydraulic character (which GAET represents with the parameter t_{90}), and timing of start of the groundwater recharge season.

5. Empirical information, whether obtained through further literature review, re-analysis of existing paired catchment data, or new field studies, is needed in order to make a determination as to whether forest harvest can significantly affect winter recharge in western Washington.

2. How do the reviewer comments change my recommendations for future work?

Taking the Executive Summary and Section 1.10.2 together, I effectively made seven recommendations. A paraphrased list is given here for reference.

Near-term research efforts should focus on making *empirical* determinations as to whether

1) Cumulative winter evapotranspiration over forest is non-negligible;

2) Vertical advection can occur over non-forest in winter, at similar rates as over forest;

3) timber harvest results in a significant change in the timing of the start of the groundwater recharge season;

4) it would be rare for t_{90} to be high enough for vegetation-conversion to result in increased probability of slope instability; and

5) a significant harvest-groundwater storage effect can be *experimentally* demonstrated in one or more basins where geology and climate is most conducive to such effect.

The SRC reviews do not lead me to change any of these five recommendations. The remaining two recommendations were

6) Determine under what site-conditions, if any, horizontal advection is likely to cause significantly elevated winter AET.

7) Postpone further development of the model as a screening tool until after the hypothetical linkage between forest practices and wet season groundwater storage is empirically substantiated.

I would restate the sixth recommendation as follows:

6) Try to better understand whether clearcut patches can create local advection effects that are significant for AET, recharge, and slope stability.

In consideration of the SRC reviews, I now believe that several model-development activities are warranted in the near-term. These are as follows.

7a) Incorporate reviewers' suggestions for model implementation and parameter values. Perform direct validation of GAETP using Campbell River forest data.

7b) Test the sensitivity of the simulated hydrology at Campbell River to uncertainty in meteorologic variables, with emphasis in vapor pressure and precipitation.

7c) As they become available, test the model on other micrometeorological data sets, e.g. Campbell River young forest plantation. Suitable data sets are those providing all the variables required for the Penman-Monteith calculation at high temporal resolution, as well as independent estimates of actual evapotranspiration.