The Sensitivity and Vulnerability of the Pacific Northwest (USA) to Climate Variability and Change: A Human Dimensions Perspective

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Introduction

Following the paper on patterns of climate variability in the Pacific Northwest (PNW) (USA) by Nathan Mantua; and the paper analyzing the impacts of climate variability on patterns of reservoir operations by Alan Hamlet, this paper completes the triptych on the integrated assessment of the impacts of climate variability and change in the region. The paper answers three questions from a human dimensions perspective:

1. How sensitive is the PNW to climate variability?
2. How adaptable is the PNW to climate variability and change?
3. How vulnerable is the PNW to climate variability and change?

This approach is taken from IPCC. WGII, "1995 Assessment and Policymakers Summary":

Sensitivity, Adaptability, and Vulnerability

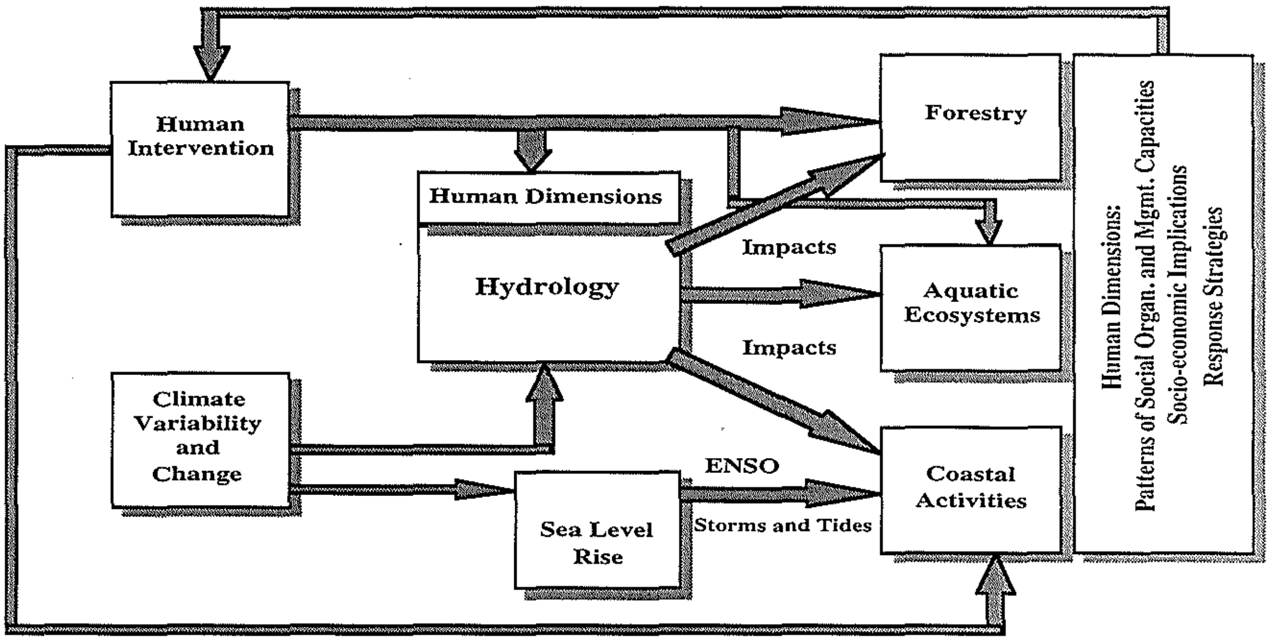
> ***Sensitivity*** is the degree to which a system will respond to a change in climatic conditions (e.g., the extent of change in ecosystem composition, structure, and functioning, including primary productivity, resulting from a given change in temperature or precipitation).
>
> ***Adaptability*** refers to the degree to which adjustments are possible in practices, processes, or structures of systems to projected or actual changes of climate. Adaptation can be spontaneous or planned, and can be carried out in response to or in anticipation of changes in conditions.
>
> ***Vulnerability*** defines the extent to which climate change may damage or harm a system. It depends not only on a system's sensitivity but also on its ability to adapt to new climatic conditions.

The analysis is divided between the present climate, which establishes the baseline for estimating societal response capacity, and the future projected climate. The paper will demonstrate that apart from increases in average regional temperature, climate change reveals itself in terms of changing patterns of variability.

Observing Regional Patterns of Climate Variability and Impacts

The conceptual approach adopted by the JISAO/SMA Climate Impacts Group to observing and assessing regional patterns of climate variability is shown in Figure 1. This figure depicts two independent drivers of impacts in the four sectors chosen for analysis, *i.e.*, hydrology, forestry, aquatic ecosystems, and coastal activities. These drivers are human intervention (or anthropogenic activities) and climate variability and change. Within the climate box two additional drivers are identified: the El Niño/Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO).

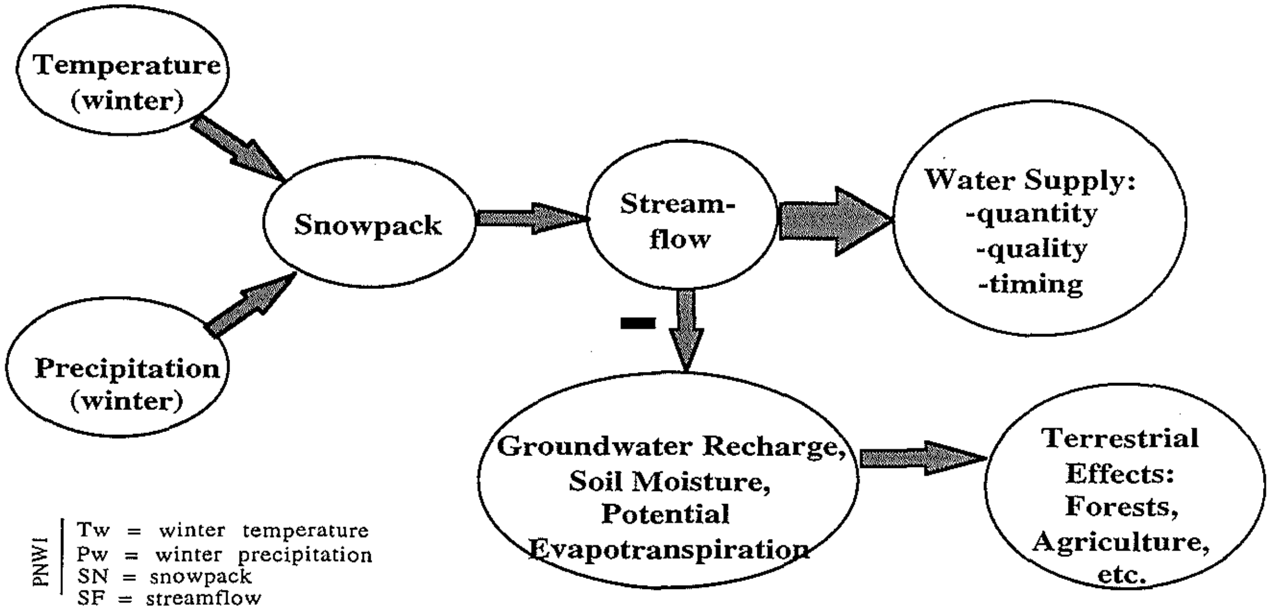
Figure 1: Approach to the Integrated Assessment of Climate Variability and Change in the PNW



Because the PNW is a snowmelt region there is a remarkable degree of coherence to the climate system since all impacts, except for those generated by sea level rise, are mediated through the regional hydrology. As a consequence, the direct effects of climate variability are modified to a considerable degree by rule curves and priorities defining patterns of reservoir operations.

The regional hydrology also determines the dominant impact pathway on both the seasonal/interannual and the decadal time scales. This pathway is shown in Figure 2.

Figure 2: The Dominant Impact Pathway



PNW1
Tw = winter temperature
Pw = winter precipitation
SN = snowpack
SF = streamflow
GWR = groundwater recharge
SM = soil moisture
spring/summer
PET = Potential Evapotranspiration

It is important to understand that the regional experience of climate variability is determined by the framework of the climate impact system and exhibited through the dominant impact pathway. Let us then assess the sensitivity of the PNW to climate variability distinguishing between the effects of ENSO and the PDO as the principal climate drivers.

How Sensitive is the PNW to Climate Variability? [Present Climate]

We begin with positive ENSO (El Niño) teleconnections highlighting only the most important impacts. We note first a significantly increased probability of summer drought with weak to moderate events (i.e. 0.5-1.5 sigma). These provide the evidence for the canonical description of El Niño impacts in the PNW, but the complete picture is more complex. Three out of 27 events (11%) are in fact "double whammies," i.e., the first year summer drought leads to significant lowering of reservoir levels and the rains do not return in the fall to permit refilling. These events have occurred only when the PDO and El Niño are in phase. For very strong El Niño events, i.e., >1.5 sigma, the PNW tends to experience near normal precipitation and anomalously warm October-June temperatures.

What impacts cascade out of the regional hydrology onto the other three sectors? As far as water supply is concerned, quantity, quality, and timing all tend to be degraded in weak to moderate events. Since streamflow declines some 13-15% on average during these events, decreased water supply reduces the system's ability to meet multi-use objectives, thereby triggering increased conflict among users: hydropower, fisheries, irrigation, transportation, recreation. Reduced supply also reduces operating flexibility in reservoir management. Decreased hydro-electric production implies the need for increased purchases of power from other regions. As supply decreases, water quality problems tend to increase.

With respect to forests, even though seedlings and not mature forests are threatened by anomalously low soil moisture, one can still observe increased summer drought stress on mature trees, especially over decadal cycles. It is not yet clear whether this stress makes mature trees more susceptible to pest infestations. Clearcutting also increases the vulnerability of young trees to climate variability on both ends of the precipitation dimension because it modifies the hydrologic network and it amplifies the potential magnitude of flood events.

For both young and mature trees, the crucial mechanism linking climate variability to disturbance regimes on both interannual and interdecadal timescales is PET. The key variable for mature tree growth is winter precipitation followed by warm spring temperatures, which define the length of the growing season. Some species require up to two years of heavy precipitation followed by a year of light precipitation and warm spring temperatures for optimal growth. Winter precipitation combined with temperature translates into snowpack for both wet sites at lower elevations and relatively dry sites at higher elevations. El Niño events therefore interrupt the optimal cycle for forest growth, but these interruptions are masked by the mature trees if the summer drought is pronounced only in the El Niño year, which is the normal PNW pattern in any case. Multiyear droughts can affect rates of mature forest growth as well as rates of forest regeneration. We have begun an investigation to determine whether "double whammies" have observable effects "on the ground."

In weak to moderate strength El Niño years that result in anomalously low snowpack and summer drought, fire risks will increase, though risks will vary by locale and forest type and along temperature/precipitation gradients. Some sub-regions will experience increased fire risks associated with El Niño while others will not. Insect outbreaks will increase where drought stress and fire risks increase. Insect outbreaks and fire will have reciprocal feedbacks that increase risks of both disturbances.

Forest growth may also be more sensitive to winter conditions than previously thought and for reasons having nothing to do with either precipitation or temperature. The crucial factor may be sunlight for photosynthesis but there are no definitive results available on this issue as yet.

With respect to freshwater fisheries impacts in weak to moderate strength El Niño years, we know that in small rivers and lakes, salmon migration and spawning are harmed by decreased summer/fall runoff and degraded water quality. In "double whammies," there is increased risk of in-river mortality for juveniles as well as temporary loss of wetlands and coastal habitat for outmigrating salmon. During years with anomalously warm coastal ocean waters smolt mortality increases tremendously in the first month of life at sea. The mortality appears to be a result of increased predation by seabirds and mackerel, increased competition for a reduced food supply, and those fish (Coho) which do survive the predation to complete the full migratory cycle return significantly smaller than usual. This means that El Niño events which produce strong teleconnections to the NE Pacific Ocean cause marked reductions in primary productivity in the ocean and consequently there is not as much food for salmonids and other top level predators as in other years.

At the Washington/Oregon coasts, El Niño years bring with them increased risk of coastal erosion if not coastal hazards (landslides and bluff failures) as results of the combined effects of increased sea level rise and the shift in the pattern of winter storms and surface winds. Erosion is enhanced if storms also hit the coast at high tide. Additional enhancement comes as a result of the loss of sediments to replenish coastal beaches since the 1980's. The latter is thought to be an anthropogenic effect, a by-product of the installation of over 100 dams on the mainstem Columbia River system (WDOE). Coastal communities also experience increased winter flooding in rivers as a result of the combination of increased SLR/storm shifts/and termination of river dredging (Johnson, 1998).

The question of coastal bluff landsliding is more complex than the problem of coastal erosion. Coastal bluff landsliding in Puget Sound is related more to winter rainfall and soil saturation, than to elevated sea levels. Coastal bluff landsliding on the Oregon coast is related to both winter rains and elevated sea levels, e.g. The Capes (D. Canning, WDOE, personal communication, 1998). Coastal bluff landsliding on Washington's north Pacific coast is poorly monitored because it occurs on undeveloped public property. Washington's South Pacific coast has no coastal bluffs to speak of, and those too are backed by undeveloped public property (D. Canning, personal communication, 1998).

Dramatic coastal erosion incidents in Puget Sound occur most frequently with northerly winds; shorelines exposed to the more common winter southerly winds tend to be well armored, whereas the shorelines with a northern exposure tend to be unarmored (due to the lower frequency of North wind erosion-producing weather events) and therefore more susceptible when there is a northerly storm. The area most at risk from coastal erosion associated with elevated sea levels is Washington's southwest coast (and similar sand spits in Oregon) due to its geologic nature. Unconsolidated sand is more erodible than is partly or well consolidated materials on Puget Sound bluffs or Oregon's coast. (D. Canning, personal communication, 1998).

When the PDO is positive, the PNW experiences decadal-scale reductions in streamflow on the order of 15-20% compared to the long-term average! Researchers are hoping to understand better the underlying physical dynamics which lead to climate anomalies like those associated with El Niño events but on a decadal timescale. One crucial link appears to be <u>sub-surface</u> sea temperatures. Guilderson and Schrag (1998) show conclusively that the 1976-77 regime shift was accompanied by major changes in the vertical thermal structure of the Eastern Pacific. Their findings are consistent with the hypothesis of Gu and Philander (1997) that the causal mechanism for the PDO's interdecadal timescale was penetration into the subtropics and the tropics of a sub-surface warm water anomaly originating in the <u>North Pacific</u>.

When the PDO and El Niño are in phase, the result is a significant probability shift for above average temperatures on both sides of the Cascades from December to March. Precipitation tends to remain below average on the East side but increases to near normal levels on the West side in strong El Niños (> 1.5 sigma).

Under La Niña conditions, the tropical influence on regional hydrology is generally the opposite of that which characterizes El Niño conditions. There is on average about 10% more precipitation than normal, for example. In addition there is significantly increased risk of winter and spring flooding relative to flood risks in El Niño and non-ENSO years, particularly in unmanaged rivers. The additional precipitation decreases the intensity of the competition for water supply among users. Hydropower production, and therefore extra-regional sales, are increased (Seattle City Light, 1996) and the system can better satisfy the demands for high flows to protect in-river salmonids. Water quality also tends to be higher.

These positive (more water) and negative (increased risk of flooding) effects then cascade through the rest of the regional system. Higher precipitation and streamflow benefit forest and rangeland ecosystems but they also increase production of vegetation which can increase fire intensity in succeeding drought periods because the increased vegetation functions as fuel for fires. Increased flooding in winter and spring generates adverse impacts on salmon habitat and egg/smolt survival because redds can be destroyed as a result of scouring by high streamflows. At the same time, La Niñas tend to produce positive impacts for coastal marine ecosystems because lower than normal SSTs lead to a less stratified upper ocean and therefore higher productivity as a function of more effective coastal upwelling. While the coastal areas are spared the combined erosion effects of increased sea level and shifts in the pattern of storms, on the terrestrial side La Niñas produce higher incidences of coastal river flooding by favoring increased likelihood of heavy precipitation events (Cayan et al, 1998).

The PDO in its negative phase increases streamflow on the order of 10-15% compared to the long term average. Anomalously cool winter temperatures combined with above average precipitation lead to anomalously high snowpack and streamflow. Negative phases of the PDO are also associated with relatively cool coastal ocean temperatures and reduced water column stability. These conditions create an enhanced ocean environment for growth and survival of Washington/Oregon Coho and Chinook salmon. There is a growing body of evidence suggesting that when ocean conditions for salmon are enhanced in the PNW, they decline in Alaska (Hare et al; 1998; Mantua et al; 1997).

We note that the maximum intensity of La Niña events in the entire instrumental record never exceeds -2 sigma compared to El Niño maximum scores of > +2 sigma. We note also that over the last two decades (1977-97), when the PDO was in a positive phase, there were relatively few La Niñas and many El Niños, including the two most intense events (1982/83; 1997/98) in the entire instrumental record.

We can therefore conclude that the PNW in an objective sense is highly sensitive to present patterns of climate variability. Perceptions of water managers in the region as revealed in interviews conducted by Miles. Callahan, and Fluharty during 1996 are congruent with the objective evidence (Callahan, Miles, and Fluharty, 1997). Water managers believed the PNW to be most sensitive to changes in five climate-related variables, *i.e.*, temperature, precipitation, sea level, water quantity (supply), and water quality. Water quality issues are most germane only to municipal/industrial supply and in-river fisheries, particularly salmonids.

How Adaptable is the PNW to Climate Variability?

Overall adaptability of the PNW to climate variability is determined by total storage capacity of the system, priorities and patterns of reservoir operations, fluctuating demand for water, and patterns of conflict between different governmental and non-governmental agencies and their constituencies. And, as IPCC WGII (1995) pointed out: "[s]uccessful adaptation depends upon technological advances, institutional arrangements, availability of financing, and information exchange."

We note that in the PNW total storage capacity is limited to 42.5 months; that priorities of the system, as shown in Table 1, have treated flood control as supreme from the 1930's to the 1990's; and that hydropower generation fell from second to third place in the 1990's, replaced by protection of fisheries. We note further that even with present climate and present levels of population growth/density there are water years in which the Columbia system cannot meet the demand which is placed upon it so that junior water right holders in Eastern Washington sometimes pay for water that they never get.

Table 1: Priorities of the Columbia Operating System

Priorities of the Columbia Operating System from ~1930's to Late 1980's	Changing Priorities of the Operating System in the 90's
1. Prevent flooding	1. Prevent flooding
2. Generate hydropower (fall/winter release)	2. Protect fisheries (BiOp spring flows)
3. Supply irrigation for agriculture (refill) Preserve fisheries (instream flow) Provide recreation, navigation (refill)	3. Generate hydropower (fall/winter releases) Provide recreation opportunities (refill)
	4. Supply irrigation for agriculture (refill) Navigation (refill)

Adaptability of the hydrosystem of the Columbia Basin under present patterns of climate variability is determined by a combination of the technological infrastructure and institutional arrangements, including those imposed by the legal system. Let us therefore consider those factors in detail. We begin with the technological infrastructure, by which we mean the reservoir system and its operating procedures as defined by the governing rule curves which, in turn, are supposed to reflect the mandated priorities.

The two most difficult problems the reservoir system of the PNW must deal with are droughts and floods. Table 2 shows the relationship between high flow events in the instrumental record and drought in relation to both phases of ENSO and non-ENSO years. High flow events, which usually bring floods in unmanaged rivers, and depending on magnitude, even in partially-managed rivers, are overwhelmingly associated with the occurrence of La Niñas. Moderate summer droughts can occur in both phases of ENSO events as well as no-ENSO years, while intense summer droughts occur only in El Niño years. "Double whammies," in which the summer drought is intense, reservoirs are drawn down, and the rains do not return in the Fall occur only when the PDO and El Niño are in phase. Additional work being done by research assistant Kristyn Gray and Alan Hamlet on "double whammies" shows that multiyear droughts, the longest of which in the instrumental record lasted 39 months, occurred when the PDO was in its positive phase, or when PDO/El Niño were in phase, or when a positive PDO was combined with a series of back-to-back El Niños (Gray and Hamlet, 1998).

Table 2: ENSO Association with Floods and Droughts in the PNW, 1878-1997

(COLUMBIA RIVER ONLY)

	High Streamflows (Floods in Unmanaged Rivers)	Droughts	1-Year Major Reductions in Water Supply	**2-Year Reductions in Water Supply - Critical Droughts	Total # Events
El Niño	0	2	12	3	26
La Niña	19	1	0	0	28
Non-ENSO	1* (Vanport Flood, 1948)	3	0	0	65

** "Double Whammies"

Let us then test the sensitivity and reliability of the system by looking for thresholds or discontinuous jumps in the management of the PNW water resources systems. Thresholds are shortcuts to impacts and occur in relation to declining streamflow or highflows.

Threshold Effects:

The instrumental record shows that summer droughts of varying intensities occur when streamflow varies between 56-76% of normal and that these events occur mainly, but not exclusively, in El Niño years. We do not have enough data of sufficiently fine temporal resolution to calibrate the effects in other sectors when streamflow falls to 56-76% below normal, but we do have the surprise finding that there are "double whammies" in the twentieth century and that these events have produced three of the most serious multiyear droughts in the PNW for the last 275 - 350 years.

Garfin and Hughes (1997), on the basis of tree ring analysis for a 275-year chronology for a forest in Oregon, show that the drought of 1928-32 is really a nine-year drought; a drought of 5-6 years occurred in the 1850's. These two represented the most severe drought events for the entire period. Using a 350-year tree-ring chronology from Mountain Hemlock situated on the Cascade Mountains and Olympic Peninsula of Washington, Dell'Arciprete et al. (1998) corroborate these findings. The interesting thing here is that the drought of 1928-32 was taken by the U.S. Army Corps of Engineers to constitute the basis of the "critical period" rule curve for the design and operation of PNW reservoirs, as a result of which the region has a 42.5 month maximum storage capacity. While 42.5 months may not seem to amount to a lot of capacity in the face of dwindling supply relative to demand, the fact is that the rule by sheer happenstance turns out to be extremely robust from the perspective of climate variability.

We think this analysis opens up two new questions for analysis: 1). what are the detailed impacts of "double whammies" in the four sectors of concern, plus the agriculture, energy, and human health sectors? and 2). what is the probability of a drought lasting longer than 42.5 months? We have launched a new investigation to answer question one; and we must turn to paleoclimate reconstructions to answer question two using techniques developed by Laird et al. (1996) to reconstruct a record of drought intensity and frequency over the past 2,300 years in the Northern Great Plains. Using a diatom-inferred salinity record from a topographically closed-basin lake in eastern North Dakota, the authors detected extreme droughts persisting for centuries between A.D. 200-370, A.D. 700-850, and A.D. 1000-1200. Patterns of climate variability clearly can change.

In the analysis of thresholds done by Alan Hamlet, two measures of performance were utilized:

- ***Reliability*** - The observed probability of no failure (units %). A high reliability means a high likelihood of meeting the objective.
- ***Vulnerability*** - The average value of the "deficit" when there is a shortfall (appropriate units). A high vulnerability means that when there is a failure, it will tend to be a severe one, whereas a low vulnerability indicates that failures will be less severe.

Using the priorities as a guide, we have done a quantitative analysis of actual operational performance from 1900-1996 based on anomalies or standard deviations above and below the long-term average, the key to which is displayed in Table 3.

Table 3: Key Performance Evaluation of Reservoir Operation, 1900-1996

Anomaly (sigma)	2.0	1.5	1.0	0.5	0	-0.5	-1.0	-1.5	-2.0
% normal	136	127	118	109	100	91	82	73	64

In reservoir operations, 90% reliability is regarded as the critical threshold (Hamlet, 1998). The reliability of McNary flows is below 90% when flow is between 110% and 100% of normal. Middle Snake Agriculture reliability falls below 90% when flows are between 100% and 90% of normal. Non-firm energy does not fall below 90% reliability until flows are between 73% and 64% of normal.

Similarly for flood control we begin to see substantial impacts starting at about 125% of normal and higher. Flat water navigation on the Snake is substantially compromised by the time flows are about 110% of normal and greater.

Based on this understanding, let us consider the information presented in Table 4. The threshold for navigation on the Snake River occurs when streamflow is 0.5-1.0 sigma above normal.

Table 4: Columbia Basin Threshold Analysis

Flood control at Columbia River Falls is never permitted to fall below 100% reliability, *i.e.*, it is completely protected; but flood control at the Dalles does have a threshold when streamflow is 1.5-2.0 sigma above normal. Firm energy production is also completely protected from any of the climate variations observed in the 1931-89 period of record.

The reliability of Grand Coulee dam for recreational purposes is adversely affected when flow is at 0.0 to -0.5 sigma; while fish protection declines at both Lower Granite and McNary when flows are at 0.5-0.0 sigma and 0.0 to -0.5 sigma respectively. The threshold for Middle Snake agriculture is at -1.5 to -2.0 sigma. Non-firm energy has a threshold of -1.5 to -2.0 sigma as well; while Upper Snake agriculture (irrigation demand) is completely protected, as are flow targets for the Hanford Reach.

Irrespective of what the legislation says, therefore, in the 1990s the most protected activities in the PNW from inter-annual variability in streamflow are: 1). firm energy; 2). flood control; 3). the Hanford Reach (recreation and fisheries); and 4). Upper and Lower Snake River irrigation withdrawals (agriculture). The least protected activities are: 1). navigation; 2). streamflow targets (fisheries) at Lower Granite and McNary dams; and 3). non-firm energy.

Institutional Arrangements:

Institutional arrangements in the PNW relative to the overriding priority of flood control clearly facilitate adaptability. This is so because there are only three major actors: the U.S. Army Corps of Engineers, the Bureau of Reclamation (BOR), and the Bonneville Power Administration (BPA). The Corps operates 22 major dams; BOR 9; and the BPA markets hydropower for all federal dams. But, with respect to flood control, there is no doubt about who is in charge of reservoir operations for all dams; its is the Corps. There are also close links on forecasts and flood control protocols between the Corps, the NOAA Regional River Forecast Center based in Portland, and the National Resource Conservation Service (NRCS) of BOR.

With respect to drought this is hardly the case. The Columbia Basin, as a natural system, is under great stress because it cannot even now satisfy all demands which humans make upon it. The consequence is increasing conflicts over the last two decades, especially between in-stream versus out-of-stream uses. As water supply decreases, conflict intensifies.

By multiplying the number of user groups over time to the Columbia hydrological system, one increases the need to shift priorities. As Callahan et al. (1997) show, coalitions form on either side of the "spill vs. fill" conflict dimension, thereby resulting in a line-up of hydropower, irrigation, municipal and industrial water supply, some recreation, and some navigational interests against environmental and commercial interests seeking in-stream protection for fisheries, other recreational, and other navigational interests. The dominance of flood control protocols in reservoir operations may benefit different interests on either side of the divide at different times but, as we have shown in the discussion of thresholds in this chapter, the operational dominance of hydropower interests means that the others must fight over what is left in the face of climate variability and other demands.

Can the system optimize water use in the region? The answer to that is a resounding no for a series of quite complex reasons. The system is very large and fragmented (103 players) at Federal, regional, state, county, and municipal levels, plus 14 Native American tribes. On top of that complexity, it is obvious that institutional design was never systematic. It was and is piecemeal and haphazard since each dam is created with its own authorizing legislation unrelated to what has gone before. Legal agreements (particularly the PNW Coordinating Agreement [PNCA]) provide the authority for coordination in a highly decentralized system and, because these agreements are never harmonized and the authority problem is never resolved, there is great inertia in the system.

Under these conditions any changes to system-wide operations require a huge bureaucratic effort, therefore short-term changes for only incremental improvements are unlikely. Furthermore, given the conflict pattern described above combined with the fact that the system cannot now satisfy all competing demands, any system-wide change will have distributional consequences. In this context, there will be no problem if the climate forecast, e.g. in a negative PDO phase, is for greater than normal precipitation and streamflow. But if, in a positive PDO phase, the forecast is for seriously declining precipitation and streamflow, the system cannot define optimal use for 103 parties with such diverse perspectives for the reasons described above. Consequently, such a forecast is likely to intensify social conflict even if it is perfect.

Another serious institutional deficiency which is a major hindrance to optimizing water use in the face of declining supply is Western Water Law, which was developed in the nineteenth century and is very resistant to change (Illahee, 1995). This law is based on the concept of the prior appropriation rule, i.e. "first in use, first in rights." This rule favors irrigation and is heavily subsidized by tax payers. This rule in its original form denies that there are any connections between groundwater and surface water and denies that water left in the stream is of "beneficial use."

In the face of legal attacks by environmentalists and even a disparate group of people seeking protection for fisheries, the rule has been amended so that the latter two denials are no longer operative. More and more opponents to the rule are relying on the provisions of the Clean Water Act, the Endangered Species Act, and the Public Trust Doctrine to erode the inflexibility of the prior appropriation rule (Johnson and Pascal, 1995). Moreover, in a case involving the Washington Dept. of Ecology vs. about 150 developers who appealed to the State Pollution Control Hearings board in 1996, the Board upheld the authority of WDOE to deny applications for rights to groundwater for the purpose of protecting state fisheries (Seattle Post-Intelligencer, July 17, 1996, A1). The Board's decision was in turn upheld by the King County Superior Court in 1998 (Seattle Post-Intelligencer, July 20, 1998, B1:2).

The shortcomings in institutional design are very hard to change because one can do so either via voluntary transfers, e.g. leasing rights, which are expensive and only temporary, or via the courts as is being done, or via State/Federal legislatures, all of whom prefer to duck the issue. There are only two routes in the courts but both are very time-consuming and expensive, i.e., litigation or a general adjudication for a watershed. Only one of the latter has been tried for the Yakima Basin, but this has been in the courts for 18 years and the experts predict another 9 years before there will be an outcome.

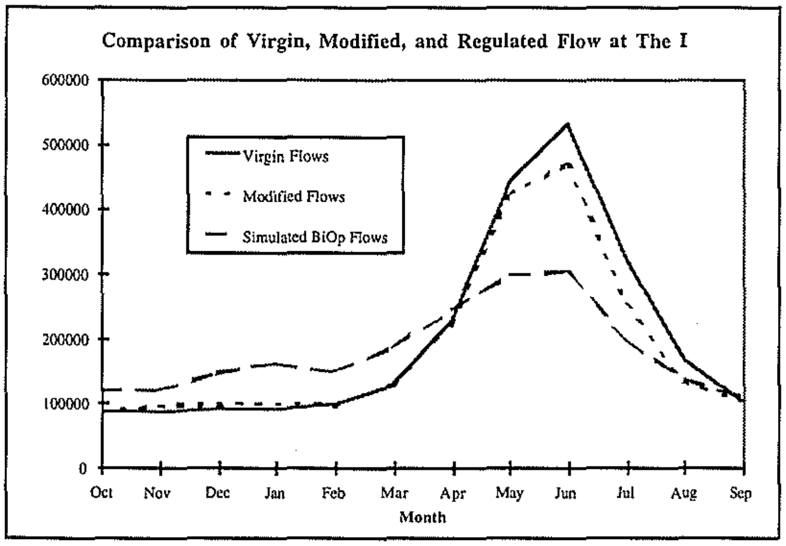
Anthropogenic Impacts as Constraints on Adaptability

Before we consider what the future climate might be like and what the implications of climate change may be relative to regional sensitivities and vulnerabilities, we need to document the anthropogenic effects on biogeochemical systems and human social systems because these are additional elements of stress operative under both the "now" and future climates. They also simultaneously create a demand for and limit to society's capacity to respond to these stresses. As such, they affect both sensitivity and vulnerability in important ways.

Hydrology:

With respect to the regional hydrology, anthropogenic changes to the natural flow regime in the Columbia River Basin are large. Figure 3 shows the average observed flow values at The Dalles for each month for Virgin, modified (diversions and evaporation), and regulated BiOp alternatives. The effects of all anthropogenic changes are reflected in the BiOp alternative. (Note that the Columbia Basin flow regime as a whole is not affected to a great extent by diversions and evaporation. The same cannot be said for sub-basins like the Yakima and the Snake where the natural flow regime is radically altered in summer by irrigation diversions.) Note also that the BiOp objectives are never achieved in August and September every year.

Figure 3: Comparison of Virgin, Modified, and Regulated Flow at the Dalles



Building dams on the Columbia has created problems with fish access to habitat (both anadromous and non-anadromous), fish transport to the ocean (anadromous only where not blocked), water temperature, and water quality (particularly dissolved gas problems). In many areas, the ecosystem has been transformed from what was once a river ecology to a dam-controlled lake ecology with primarily resident, non-anadromous fish stocks. There are now no anadromous fish runs above Grand Coulee dam on the main stem of the Columbia or above Hells Canyon Dam on the Snake. For this issue, the relative importance of anthropogenic changes and climate is completely clear-cut. The human use has completely eradicated the fishery, and climate change can have no additional effect. The building of the dams on the Columbia River, and the way they are used has transformed the Columbia from a river ecosystem to a series of dam-controlled lakes. While the overall effects to humans associated with this change are not clear, it is clear that this change in the ecosystem is entirely anthropogenic in nature, and that any effects due to climate change are secondary in this sense. Climate variations may exacerbate or mitigate effects associated with anthropogenic changes to the Columbia, but without removal of a large number of dams, the Columbia will not function again as a river ecosystem regardless of any changes due to climate shift. A strong case can be made that human activities affecting land use, hydrology and water quality such as point and non-point source waste water inputs, logging, agriculture, urbanization, and mining are believed to have major implications for the ecological health of PNW river basins.

Forests:

Anthropogenic impacts on forests have been immense in terms of both direct and indirect effects. Direct impacts of humans include: 1). conversion to anthropogenic ecosystems (urban, agricultural, etc.); 2). simplification in structural complexity, species diversity; and 3). reduction in carbon sequestration. Hence, there have been 1). dramatic reductions in overall acreage of forests as they have been converted to developed metropolitan uses and agricultural lands; 2). conversion of the majority of the remaining forests from natural systems with high levels of structural complexity and species diversity to highly simplified plantations; and 3). consistent with the preceding comments, large changes in functional capabilities of the remaining forests such that carbon sequestration has been greatly reduced from presettlement levels with a decrease in the ability of forests to moderate hydrologic and geomorphic processes (i.e., erosion). Another way of viewing the result is a significant reduction in the ability of forests to provide amenities and non-market goods and services.

Human activities have also had major indirect effects on forests and forest functions, particularly through effects on forest disturbance regimes. Dramatically altered forest disturbance regimes are an example. Fire suppression activities in forests normally subject to frequent, light to moderate fires have resulted in large increases in forest fuels and the potential for catastrophic fire and insect epidemics. In other forest landscapes, timber harvest has created opportunities for massive blowdown of trees by windstorms. Insects and diseases introduced to North America from other continents have resulted in massive mortality of individual species and harvests; this process which began about 100 years ago continues to the present, as evident from the destruction of Eastern hemlock forests by the hemlock adelgid which is believed to have been introduced from Europe via wood pulp imports!

The intensity of the anthropogenic disturbances is far beyond any disruptions of forests which have been experienced in the last several millennia due to climate fluxes. They also exceed what is likely to occur under most current climate change projections.

Aquatic Ecosystems:

Physical alteration of freshwater rivers and streams by dam construction, channeling, and the like increases the severity of flooding as its major effect because it eliminates riparian forests and vegetation, thereby increasing runoff. In addition, the sediment load in the stream is increased and biological productivity decreases as a function of flood plain loss. Often there are pollution impacts as well from point and non-point sources. And water transfers, especially for irrigation or municipal and industrial uses, may combine with climate variability (i.e., fluctuations in precipitation patterns) to reduce the flow regime for ecosystem purposes.

In estuaries, pollution from point and non-point sources is also a problem but three types of impacts are most serious: a). loss of wetland and marsh as a result of development; b). changes in the freshwater/saltwater interface affect the range of biotic organisms that can inhabit the estuary;

and c). exotic species which are introduced to an area may find conditions which facilitate rapid propagation to the detriment of indigenous species.

In the marine environment the most serious anthropogenic effect is "top down" over-harvesting of upper-level predators stimulating artificial changes in the structure of the resident ecosystems. But pollution effects are felt here as well, especially in the coastal ocean.

Coastal Activities:

Coastal zone managers tend not to distinguish the climate signal from man-made changes in the natural environment because the latter loom so large. The major anthropogenic impacts in the coastal zone tend to come from a combination of factors:

a). clear cutting of forests which significantly increases the sediment load carried by rivers;

b). halting of river dredging to the extent that the frequency of spring flooding increases dramatically; and

c). increases in residential construction and public infrastructure given the increasing density in coastal populations and rapid expansion of the coastal recreation and tourism industry. As communities expand, they tend to proliferate armoring as a response to coastal erosion thereby making the systemic problem worse and decreasing the area for beach migration landwards.

The planning horizons of coastal planners and managers also constitute another anthropogenic impact. These horizons, which range from 5-50 years, bias coastal managers against perceiving their systems as being sensitive to interannual variability. Long time horizons also constrain system adaptability on seasonal/interannual timescales as well. In addition, given the uncertainties generated by the gross resolution of the GCMs, which do not allow magnitudes of impacts to be projected with any degree of assurance, managers remain unsure how their systems would be affected and whether the climate signal could ever be separated from the anthropogenic signal. There is a self-fulfilling prophecy here since, once large-scale development occurs, vulnerability increases because management cannot respond effectively to threats from climate variability and change.

How Vulnerable is the PNW to Climate Variability and Change? (The Present Climate)

The perceptions of regional water managers concerning regional vulnerability to climate variability are displayed in Table 5. These results are tabulated from a survey conducted by Miles, Callahan, and Fluharty in 1996. They show that vulnerabilities, not surprisingly, are associated with climate extremes. However, what is not so obvious is that perceived vulnerabilities are also indirectly linked to where people stand on the "spill versus fill" dimension to conflict.

Table 5: Ranked primary vulnerabilities related to climate variability in the Columbia River Basin.

Water Management Vulnerability of Concern	Number and Percentage of Respondents Considering This Vulnerability Major (N= 25)
Drought	20 [80%]
Flooding	15 [60%]
Low storage capacity in reservoirs	12 [48%]
Decline in fisheries stocks and habitat	8 [32%]
Water quality degradation	5 [20%]

Out of the twenty organizations that listed drought as a primary vulnerability, many stated that this vulnerability had increased as result of the fisheries requirements in place. These included managers at Tacoma Power and Light, Seattle City Light, and the NRCS whose management actions were directly affected by the drought of recent years. The Seattle Water Department noted that the drought of 1987-1992 threatened municipal drinking water supplies. That problem also created more conflicts with protecting streamflows for fisheries and recreation benefits.

Drought exacerbates conflicts between instream users and out of stream users, worsens water quality problems, and has a negative impact on water rights disputes. It affects every use sector in the assessment, as shown in Table 6. Each sector has something to lose in a drought situation, and the benefits of climate forecasts to address this problem merit greater attention.

Table 6: Rank of Importance of Each Vulnerability for Sectors

Flood Control	Forecasting	Fish and Wildlife Management	Water Quality and Watershed Management
1. Flooding 2. Storage 3. Fisheries, Drought, and Water Quality	1. Flooding and Storage 2. Drought 3. Fisheries	1. Drought 2. Fisheries 3. Flooding 4. Storage/Water Quality	1. Drought 2. Flooding 3. Storage and Water Quality
Navigation	**Managing Multiple Water Uses**	**Irrigation**	**Hydropower**
1. Drought 2. Flooding	1. Drought 2. Flooding and Storage 3. Water Quality	1. Drought 2. Fisheries, Storage, and Flooding	1. Drought, Flooding, and Storage 2. Fisheries

How does drought affect each sector? As shown by Table 6, it is the top ranking vulnerability for all sectors except forecasting and flood control. The hydropower industry can lose economically because of lost generation capabilities and the cost of buying power outside of the Columbia River system. Hydropower and irrigation both lose politically because conflicts between fisheries become more serious as the water budget devours their generating and irrigating capacities.

Droughts exacerbate low streamflow problems for salmon, and water quality problems as well. Drought is the only vulnerability that registered on the transportation sector, because of its implications for barging operations. Their main concern is for the end of the summer in extreme drought years, but they felt they could mitigate impacts by rearranging their shipping schedules. There is also some vulnerability to the transportation industry due to climate impacts on wheat growers, who generate a demand for its services (Pacific Northwest and Waterways Association [PNWA], 1996).

The threat of drought is also perceived as a problem based on inadequate storage in the reservoir system. Unlike the Mississippi or Colorado Rivers, the Columbia River can store less than 40-50% of its annual runoff in reservoirs (Northwest Power Planning Council [NPPC], 1996). Inadequate storage was recognized as a major vulnerability by 12 out of 25 managers, all of whom have reservoir operational responsibilities.

The time scale of drought and storage vulnerability ranged from interannual to decadal, which may indicate both a loose definition of drought and vulnerability, as well as lack of knowledge about where the vulnerability actually becomes critical. For some users, such as at the Bureau of Reclamation in Yakima, a one year drought can hurt its dependent users because the storage capacity is inadequate for demand. At the Bureau of Reclamation in Boise, however, managers there felt that their drought threshold was 10 years. This contrasts with the NPPC view that a 10 year drought would be a "nightmare." For the BPA, a drought over a year long causes significant problems for generating power.

Despite the fact that much of the reservoir system was originally designed for flood control, flooding was viewed as a major vulnerability by 15 out of 25 managers interviewed. The winter of 1996 witnessed significant flooding in the Portland region, which undoubtedly put a focus on flooding during our study. The increased impacts of flooding relate to land use practices, such as forestry and increased impervious surface area, as well as climate variability. In addition, more of the flood prone areas have been developed, putting people and property in harm's way.

Floods are viewed as a vulnerability by hydropower organizations because they have major responsibilities to control the reservoir levels to compensate (Seattle City Light [SCL], 1996). As discussed above, reservoirs are drawn down for flood control in the fall to make storage for precipitation. Hydropower organizations would prefer to keep them high if the flooding risk is low so that they can use the storage for power generation. If accurate climate forecasts provide a good prediction of fall precipitation, hydropower organizations and the Corps may be able to manage the storage more efficiently for both flood control and hydropower needs (SCL 1996).

When reservoirs are spilled to make room for flood storage, the spillage does not generate power and also causes water quality problems, including dissolved gases and high turbidity. Again, irrigation interests have a common concern with hydropower because they would also like to store more of the fall precipitation for use in the following growing season (BOR 1996).

While storage vulnerabilities were primarily associated with drought risks, the Corps also views storage as a flood related vulnerability. If the flood forecast is below actual conditions, the reservoirs may not be capable of holding it all back. This was the case in the Vanport flood in 1948 where the flood maximum was 50% higher than the forecast, and could not be controlled. Thirty eight people died, and the town of Vanport was destroyed (White 1995).

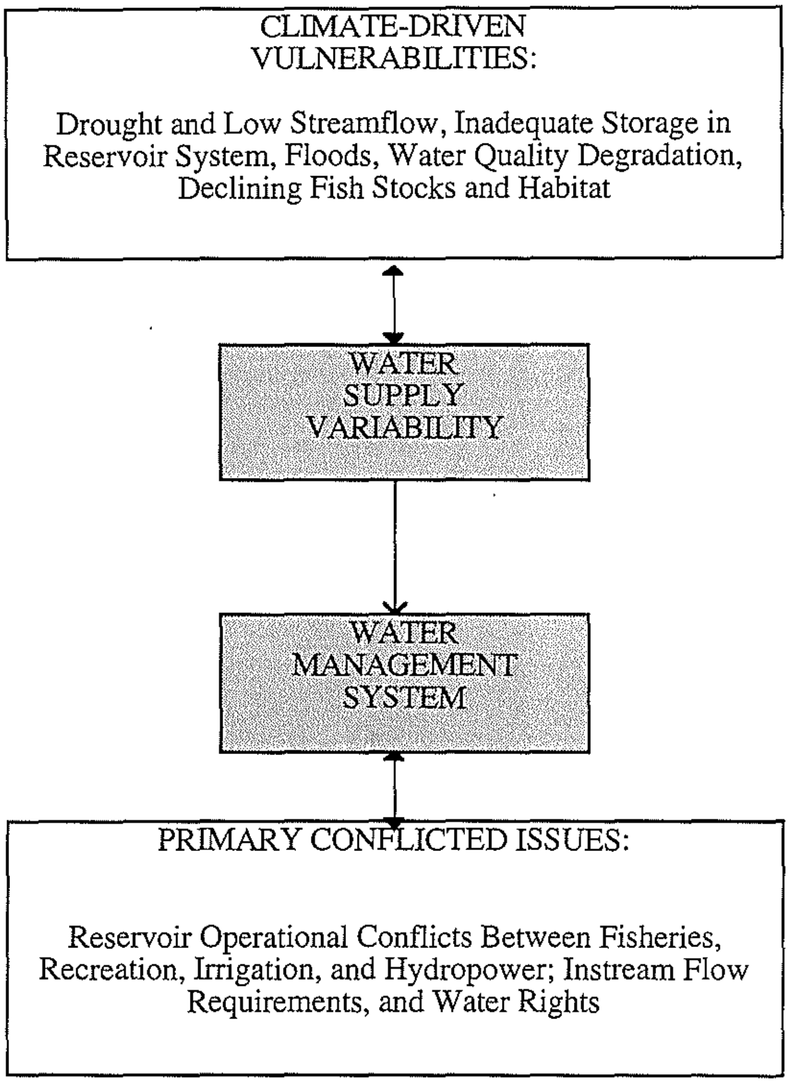
While fish are highly vulnerable to climate variability, only eight managers saw them as a major climate related vulnerability in the system. These included managers in fish and wildlife sectors, who perceived the vulnerability as negative effects of both environmental and management conditions impacting the salmon stocks. The sympathy was not focused on salmon, however, for managers in hydropower, flood control, forecasting, and irrigation. They viewed the decline in fisheries as a vulnerability, but for different reasons. They felt that the major vulnerability resulted from the inflexible changes in the management requirements that are designed to help restore fish stocks.

Five out of 25 managers felt that water quality was a major climate vulnerability. All of them had fish and wildlife, water quality, or watershed management responsibilities. The three primary types of water quality problems that were discussed include overly warm temperatures, (which are mainly a problem in summer), dilution of pollutants, and turbidity. All three are strongly affected by climate variables including temperature, precipitation, runoff, and the frequency and severity of storm events.

It is not surprising that in a river system, all of the uses, conflicts, and vulnerabilities are inter-related. The parallel vulnerabilities that match the conflicted issues, as shown on Figure 4, illustrate how much of a role climate variability plays in river politics.

The tight relationships between the conflicted issues and vulnerabilities indicates that addressing vulnerabilities is not a simple matter of finding a solution. Alternatives result in winners and losers situations, and therefore are difficult to implement. Yet, the connections have a bright side in that they show how climate forecasts may be used to help prepare for drought years and flooding years. This may in turn lower the level of conflict for streamflow issues exacerbated by low water supply.

Figure 4: Parallels between issues and vulnerabilities to climate variability



The Sensitivities and Vulnerabilities of the PNW to Projected Future Climates

Throughout this discussion, we will use a specific scenario of future temperature and precipitation changes in the PNW to frame our discussion of the impacts of future climate change on the region. However, we will place much of the emphasis on vulnerabilities. The climate scenario that we use is taken from a GCM simulation of future climate, performed by a major GCM modeling center (the Max Planck Institut für Meteorologie, Hamburg),[1] interpolated to the regional scale. While MPI's global climate predictions agree in general with climate predictions made by other GCMs, agreement does not imply correct simulation of future climate. In addition,

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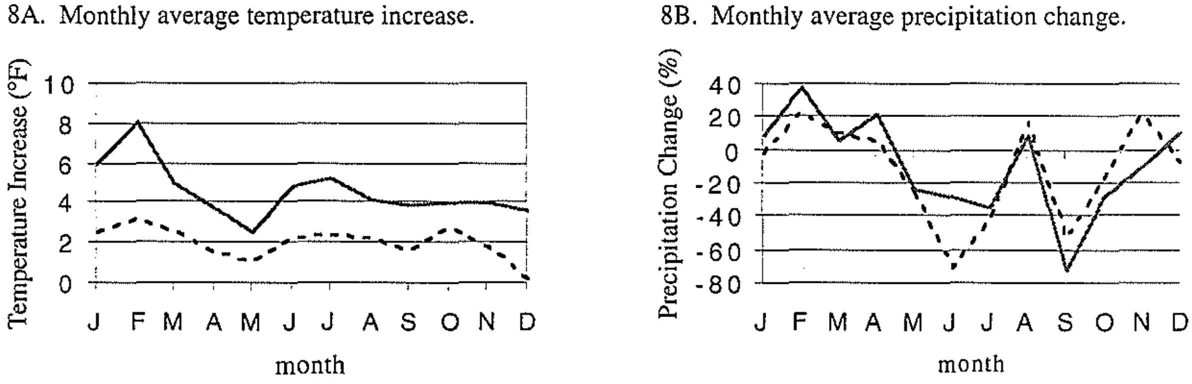
[1] The model simulation was a time-evolving, transient climate simulation using a coupled ocean-atmosphere a GCM (MPI model ECHAM1-A; Cubasch *et.* al., 1992). The model was forced with increasing emissions of greenhouse gases using emission scenario IPCC IS90a (=1%/year as CO_2). This model run is one of several archived by the Intergovernmental Panel on Climate Change (IPCC) at the National Center for Atmospheric Research in Boulder, CO for use in integrated assessments.

predictions made by different GCMs usually differ more substantially at the regional level; a different GCM would not predict the same scenario of climate change for the PNW. The scenario chosen as a basis for discussion is *plausible* in light of our current understanding and computing capabilities, but should not be considered to be a *prediction.* The paper by Hamlet compares the output of the MPI model with two other GCM's archived by the IPCC for integrated assessments, *i.e.*, the U.K. Met. Office Model (UKMO) and the Geophysical Fluid Dynamics Model (GFDL). We will refer to the results of this comparison as well.

Under the MPI climate scenario, the PNW would experience warmer, wetter winters and warmer, drier summers (see Figure 5). Annual average PNW temperatures would increase 1.1°C (2°F) by the decade 2020 and 2.5°C (4.5°F) by the decade 2050. The warming would be fairly uniform over the course of the year, with slightly more warming during the winter (Left panel, Fig. 5). Because of the thermal inertia of the climate system, temperature is expected to continue to increase beyond 2050, even if atmospheric concentrations of greenhouse gases were stabilized by that time. Under the MPI scenario, precipitation would increase somewhat during the wintertime and decrease during summers (right panel, Fig. 5), although projected precipitation changes are less certain than changes in temperature.


8A. Monthly average temperature increase.

8B. Monthly average precipitation change.

Figure 5: Average changes projected for the PNW in 2020 (dashed lines) and 2050 (solid lines) under the MPI climate scenario. (A) monthly average temperature increase; °F. (B) Monthly average precipitation change; % of current precipitation. Precipitation changes are a spatial average of fractional change in precipitation.

The model scenario indicates only how regional *average* temperature and precipitation might change; it doesn't address how climate variability would be affected by climate change. GCMs predict that climate change will lead to a decrease in the daily range of temperature in most regions. Overall, warming is expected to lead to an increase in the occurrence of extremely hot days and a decrease in the occurrence of extremely cold days. Climate change may also result in an increase in precipitation intensity, or extreme rainfall events. These predictions are less certain than projections of average changes in temperature and precipitation and may or may not specifically apply to the PNW. It is currently impossible to predict whether there will be future changes in storminess. Although GCMs currently project gradual climate change, there is a possibility that the climate system may respond in surprising and/or sudden and unforeseen ways. (IPCC 1995, vol. I; Broecker, 1987 and 1997).

Much of the variability in PNW climate results from variations in the wintertime position and intensity of the Aleutian Low pressure system. Characteristics of the Aleutian Low have been linked to interannual fluctuations in the tropical ocean-atmosphere system (ENSO) and interdecadal changes in the Pacific Decadal Oscillation (PDO). Both ENSO and the PDO, as we have seen, affect the delivery of water to the PNW (via precipitation and river runoff). How climate change might affect the frequency or intensity of these climate oscillations remains an open, albeit critical, question.

As noted, past climate variability has caused a chain of impacts in the PNW, beginning with the region's hydrologic cycle and spreading to affect the disparate areas of forests and rangelands, aquatic ecosystems, and coastal activities. What follows is a summary of our current understanding of the ways in which each of these four dimensions is vulnerable to future greenhouse gas-induced climate change. All of these systems are already under a great deal of human-induced stress. While the additional stress brought by climate change may be small in comparison, the combination of climate change with past and current stresses may result in increased vulnerability. Incorporation of an understanding of regional vulnerabilities into management planning will be important, both to prepare for climate impacts and to minimize aggravation of such impacts by related human activities.

Quite apart from vulnerabilities, will climate change of the magnitude predicted create opportunities for and in the PNW? Obvious examples exist in the realm of agriculture, for example, where increasing temperatures may lengthen the growing season, increasing productivity in this region. Opportunities are also likely to arise in the arena of energy production. The share of Northwest electricity provided by hydropower is likely to continue to decrease in the future, necessitating an increase in the amount of power provided by other sources. In view of the current international debate and the possibility of future regulation of CO_2 emissions, alternatives to fossil fuel-powered energy production and transportation may become increasingly attractive. This suggests openings for development of alternative energy sources and associated technologies as well as for the development of more and efficient technologies.

The changes which are anticipated in the eight sectors analyzed in a regional workshop with stakeholders are summarized in Table 7 (see Snover, Miles, and Henry, 1998).

Table 7: Major Expected Climate Change Impacts in the PNW: Vulnerabilities and Opportunities

HYDROLOGY & WATER RESOURCES*

West-side rivers...

- need for more deliberate spillage in fall/winter and possibility of decreased water supply in summer
- lower summer flows and increased failure to meet minimum instream flow requirements would be detrimental to fisheries protection
- increased flood frequency
  - uncontrolled river systems are especially vulnerable to larger flood peaks that may occur with climate change (lack of existing control mechanisms make mitigation currently impossible)

Columbia River Basin...

- decrease in annual run-off
- peak flows occur earlier in the year (~1 month earlier at The Dalles)
- increased competition among major users of the river system: hydropower production, fisheries protection, irrigation water supply
  - increased legal battles over water rights
- decreased hydroelectric energy production capacity and reliability
  - failures to meet current levels of firm energy production requirements would occur more often, be larger and last longer
  - need for additional power sources
- increased difficulty of providing water to meet minimum flow requirements for fisheries protection
- less water available to satisfy irrigation demand

\+ need for food storage in the Columbia River reservoir system would be reduced; *i.e.*, flood protection along the main stem of the Columbia and Snake rivers would be enhanced

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[*] Climate change impacts on hydrology and water resources were examined using hydrologic and reservoir models of the Green River (Tacoma, Washington's water supply system) and the Columbia River Basin, driven by the temperature and precipitation changes predicted by the regional climate change (Max Planck) scenario.

In general...

- – reduced ability to meet multi-use objectives in systems with a variety of constraints
- – reduced operating flexibility and reduced ability to respond to interannual and intra-annual variability in flow in heavily constrained systems (*e.g.*, Snake River, Yakima River, Cedar River)
- – moderate elevation basins could experience radical shifts in total system storage and flow regime due to snow pack shifting to higher elevations (*e.g.*, Cedar River Basin-Seattle water supply system)
- – suburban development potential and the ability to respond effectively to increasing urban and suburban water demand may be impacted
- – glacial melting may influence low-flow hydrology in some areas

FORESTS & RANGELANDS

- – increased drought stress
  - – drought stress increases tree susceptibility to pest outbreaks and increases risk of wildfires
- – forest zones shift up in elevation and northward
  - – reduced areal extent of productive forest land
  - – may make lower elevation, currently dry locations (on the lower east slopes of the Cascades, for example) inhospitable to forests in the future
- – increased pest outbreaks
  - – warmer temperatures expand pest ranges and/or accelerate pest life-cycles
- – increased risk of wildfires and increased fire intensity
- – loss of biodiversity, resulting from
  - – environmental shifts outpacing species' migration rates
  - – loss of habitat due to catastrophic disturbances; fragmentation
  - – ecological reserves, with their fixed boundaries, are especially vulnerable
- – tree seedlings are especially sensitive to temperature increases and may not be able to establish and grow in the same place under altered climatic conditions (more of a concern to preserves than to managed forests)
- – decreased forage quality of rangelands
- – increased rangeland invasion by exotic species
- – possibility of increased rangeland wildfires
- + upslope expansion of rangelands on east slopes of Cascades

- +/– forest ecosystems would consist of new combinations of species due to species-specific response to climate change and altered patterns of temperature and precipitation
- +/– rangeland ecosystem composition would change, depending on the interplay between grazing, fire, pests and the shrub/grass/exotic balance

AQUATIC ECOSYSTEMS

- – freshwater fisheries, especially in small rivers and lakes, are most vulnerable to climate change
- – west-side salmon migration and spawning harmed by decreased summer and fall run-off in West-side rivers
- – fish habitat and egg-smolt survival may be harmed by increased wintertime river flows
- – increased difficulty of providing adequate water flow for fish protection in the Columbia River Basin
- – loss of wetland habitat, including wetlands created by past agricultural irrigation projects, due to lower summer base flows on rivers and more efficient irrigation
- – loss of coastal habitat for outmigrating salmon, spawning oceanic species, animals and sea birds

- + stimulation of growth and expansion of ranges of warm-water species
  - + especially near current northern boundaries of species' ranges

- +/– effects of climate change on marine fisheries are uncertain as they will most likely be felt via impacts to North Pacific atmospheric circulation and consequent changes in ocean circulation patterns (which cannot currently be predicted) rather than via any direct heating of the ocean

COASTAL ACTIVITIES

- permanent inundation of coastal areas, beaches, wetlands, and estuaries due to sea level rise
  - increased loss of wetlands between existing and future coastal development and rising seas
  - landward shoreline migration
  - increased erosion rates/events
  - loss of habitat for migratory birds, fish, shellfish and water fowl
  - increased saltwater intrusion into freshwater aquifers
- landslides and bluff failures due to increased wintertime precipitation and any increase in frequency and/or severity of ocean storm events or changes in storm direction
- increased coastal flooding events due to sea level rise, altered hydrological/precipitation cycle and any increase in future storminess
- vulnerable areas:
  erosion: SW WA coast; central OR coast
  flooding/inundation: south Puget Sound

+/– physical oceanographic changes (*e.g.*, upwelling rates, sea surface temperatures) will impact the coastal zone
+/– altered productivity of coastal systems
+/– changes in species distributions and abundances
+/– impacts on ecological processes and functions

AGRICULTURE & GRAZING LANDS

- decreased irrigation water supply coincident with increased water need in warmer, drier summers
  - increased competition for water among agriculture, power production, fisheries
- decreased grazing/rangeland productivity and shorter range season due to drier summers
- decreased production of grain crops from marginal (lowest rainfall) dryland areas
- increased crop heat stress and decreased yield stability
- decreased forage nutritive quality
- increased agricultural and livestock pests
- stimulated weed growth
- increased flooding and soil saturation in low-lying river valley or coastal areas west of Cascades
- economic forces may force low-value crops and farms from the system as demand for water increases and/or energy prices increase
- social impact on rural communities where agricultural production is disrupted

+ extended growing season due to increased temperature
+ improved crop growth and yields due to increased CO_2 -- where cost-effective irrigation water is available or where soil moisture is not limiting
+ productivity in Pacific Northwest may increase (from more growing degree days and increased CO_2) while productivity in other regions may decrease
+ possibility of greater crop diversity
+ CO_2 anti-transpirant effect may increase water efficiency in dryland areas
+ possible improved winter wheat production in intermediate to high rainfall dryland areas
+ possible productivity increases in irrigated areas, due to possibility of double cropping or longer maturing crops

HUMAN HEALTH EFFECTS

- changes in patterns of infectious diseases
  - increase in vector-borne diseases, resulting from an expansion of pest (*e.g.*, ticks) ranges and/or an acceleration of pest life-cycles
  - disease migration via human population migrations
- increased water-borne health problems
  - contamination of drinking water by saltwater intrusion

  - leaks from underground hazardous material storage tanks or landfills with rising water tables in coastal areas
  - increased paralytic shellfish poisoning events (linked to warmer than average sea surface temperatures)
  - possible increase in freshwater cyanobacteria (blue-green algae) in calm water expanses (lakes/reservoirs)
- possibility for increased photochemical smog production (due to increased temperatures and altered weather patterns)
- mental health concerns (possibility for profound social/economic distress in subsequent generations if status quo continues)

+/– decrease or increase in mortality due to altered future weather patterns

+/– potential changes in aero-allergens causing asthma and rhinitis (hay fever)

ENERGY PRODUCTION & UTILIZATION

- decreased capacity for hydroelectric power production in the Columbia River Basin
  - models predict reliability of meeting current firm energy production requirements decreases from 96% to 89% in 2020 and 82% in 2050; average shortfall increases by a factor of 8.5
  - models predict reliability of meeting current levels of non-firm energy production decreases from 96% to 88% in 2020 and 86% in 2050
  - competition for water resources would increase among hydropower production, irrigation supply, and fisheries protection
  - will be exacerbated by demand increases due to population growth
- possibility for increased energy costs
  - impacts industries such as aluminum production in PNW which depend on a cheap and dependable source of electricity
- possibility of less efficient electricity transmission systems
- future national/international agreements may limit CO_2 emissions, impacting transportation and/or energy production/utilization sectors

+ increased opportunities for development of alternative energy sources and associated technologies
+ increased market for energy-efficiency technologies

URBAN CENTERS

- decreased reliability of energy supplied by hydroelectric power production in Columbia River Basin
- possibility for increased flooding and landslides
  - environmental impacts on buildings and infrastructure
- public health concerns of increased air pollution and water-borne health problems
- altered sewage treatment plant outfall hydraulics and drainage issues, especially in coastal areas
- increased uncertainty in planning for meeting future energy and water demand
- possible negative impacts to primarily resource-based economies (forestry, fisheries and agriculture)
- possibility for decline in "quality of life" factors including skiing and other recreation and tourism

+ opportunity for stimulating economic growth by attracting alternative energy and energy-efficiency industries

+/– impacts to the economy of the Pacific Northwest vs. economic impacts to other regions

+/– migration to Pacific Northwest from other more stressed parts of the world

Comparing the Model Runs

The results of comparing the MPI/UKMO/GFDL GCM runs presented in the paper by Alan Hamlet show *different rates of warming and different precipitation patterns associated with the same levels of global warming. However, all of them predict global temperature increases in excess of 1.16°C by 2050 and, irrespective of differences in precipitation, all of them predict higher flows in the winter months and lower flows in the spring, summer, and fall months.* For a snowmelt system which depends critically on winter snowpack for each year's streamflow, these results translate into a prediction of substantially less snow and more rain in the winter months.

This prediction would imply a higher probability of rain on snow events and therefore a higher probability of winter floods. Hydropower revenues would increase in winter as a result of larger reservoir releases but water supply reliability would be degraded by this earlier runoff, especially for smaller reservoirs (Lettenmaier et al., 1992). The shortfalls in supply would be so great as to render ineffectual increasing the efficiency of reservoir operations as a means of mitigating degraded reliability of water supply. Because potential evapotranspiration would increase all year with the peak shifting to late spring/early summer, significantly reduced soil moisture in summer would adversely affect both agriculture and immature forests. Degraded reliability of water supply would affect a variety of sectors on all dimensions, *i.e.*, quantity, quality, and timing.

Conclusions

With respect to the present climate, we have shown that the PNW is highly sensitive to climate variability as determined by a combination of ENSO and the PDO. The effects, positive and negative, tend to be amplified whenever the PDO and ENSO are in phase. The regional hydrology is the regulator for the widest range of impacts and the rule curves determining present patterns of reservoir operations are robust within patterns of climate variability currently experienced. However, the system appears to be approaching its upper limits in satisfying competing demands and conflict between in-stream and out-of-stream uses is intensifying greatly.

In spite of legislation mandating greater protection for fish, our threshold analysis shows that reservoir operations do not always reflect these mandates. It is worth repeating that firm energy and flood control are the most protected activities in the mainstem Columbia. Fisheries enjoy very high levels of protection only in the Hanford Reach area and, outside the mainstem Columbia, agriculture enjoys high protection in the Upper and Lower Snake River. Conversely, the most vulnerable activities to date are navigation, fisheries at the Lower Granite and McNary dams, and non-firm energy.

Adaptability on floods is high in the mainstem Columbia and in other managed rivers, given the existence of centralized authority, technological infrastructure, and good working relationships between the dominant players. No direct adaptation is possible in unmanaged rivers because flood control is simply not possible. Inappropriate patterns of human settlement will respond only as a combined function of changes in governmental policy as practiced by the Federal Emergency Management Agency (FEMA), changes in understanding and lending policies of the insurance industry and banks, and changes in land-use policies adopted by municipalities and states.

Adaptability in the face of droughts is extremely limited. As demands for water supply exceed the capacity of the system, conflict increases and the system lacks the necessary authority at the center to optimize declining supply. This absence of authority is exacerbated by the institution of western water law developed in the late nineteenth century (the Prior Appropriation Rule).

Vulnerabilities under current patterns of climate variability are greatest in relation to floods and droughts and particularly so when the PDO and ENSO are in phase. The greatest vulnerability of the region is to multiyear droughts in excess of 42.5 months, which is currently the maximum, storage capacity of the system. We know that such a drought has not occurred within the last 350 years but on one occasion the PNW has experienced a drought of 39 months duration (Gray and

Hamlet, 1998). Vulnerabilities to both droughts and floods represent additional stresses on a system already highly stressed by anthropogenic activities.

With respect to the future climate, both sensitivity and vulnerability increase to 2050. All models predict the same patterns of changes to climate variability even if they differ in the magnitudes of the changes. The result is increased probabilities of winter flooding and summer droughts simultaneously with population growth and development. We note that the Seattle City Council is predicting an increase of two million people in the King County region alone by 2040. Greater population densities also imply fueling the fire of expanding social conflict over water supply.

The questions to be posed are: will El Niño events increase in a warmer world and, if so, will the probability of multiyear droughts increase as a result? We cannot answer the first question at the present time. <u>But if the answer turns out to be in the affirmative, then the answer to the second question will be in the affirmative, when the PDO and El Niño are in phase</u>. Even without multiyear droughts in excess of 42.5 months, at much higher levels of demand the system will be experiencing something in the range of 20-30% less water supply than is currently available.

Because vulnerabilities increase as adaptability decreases, we anticipate that increasing scarcity will force the pace of policy innovation. What then can we do when the ecosystem and the economic health of the region will face such dire threats?

IPCC, 1995, II recommends adoption of two overriding policy objectives to govern management of water resources in the face of increasing social vulnerability engendered by climate change:

1. **reward efficient water use;** and
2. **increase institutional flexibility.**

We endorse these objectives completely.

How might they be achieved? Kaczmarek et al. (1995) recommend some combination of the following suite of policy alternatives:

1. Direct measures to control water and land use.
2. Indirect measures affecting behavior.
3. Institutional changes for improved management of resources.
4. Improvement in the operation of water management systems.
5. Direct measures increasing the availability of supply.
6. Measures that improve technology and the efficiency of water use.

The Office of Technology Assessment (1993) provides its own suite of policy alternatives at a lower level of generality than Kaczmarek et al. (1995):

1. *Create water markets via use fees and adequate pricing;
2. Facilitate water transfers within and across state boundaries;
3. *Revise the tax code to facilitate conservation investment;
4. *Allow state revolving-load funds to be used for conservation investments;
5. *Tie funding of state water projects to improved efficiency in management and consumption.
6. Encourage adoption of risk management/minimization practices to mitigate drought effects.
7. Encourage water conservation in federal and state facilities.
8. * Require demand management via modifying rate structures, reducing landscape use of water, modifying plumbing & irrigation systems to increase efficiency, educational programs & metering.

The asterisks in the list above indicate those policies that we think might have particular applicability to the PNW and are therefore candidates for detailed evaluation in the future.

In the OSTP/USGCRP Regional Workshop for the PNW, held in July 1997, water managers from the region articulated their own suite of policy options to meet the challenges of climate variability and change:

1. Build new energy capacity using conventional and gas turbine technology to replace lost hydropower resources.
2. Increase cooperation, coordination, and information sharing to allow increased effectiveness of response to unknown climate effects.
3. Move people out of flood plains in uncontrolled basins as risk increases.
4. Improve system robustness and flexibility of water resources by connecting water supply systems with different characteristics. (Example given was the proposed Tacoma/Seattle intertie).
5. Increase use of groundwater for water supply (unknown impacts of this change).
6. Develop and use groundwater recharge schemes to mitigate changes to the hydrograph affecting agriculture water supply.
7. Increase the cost of water (particularly in subsidized areas where demand is high).
8. Continue to develop conservation and other demand reduction schemes for agricultural and municipal and industrial water supply (counter-intuitive changes to streamflow as a result of return flow for agriculture were mentioned).
9. Desalination plants.
10. Waste water reuse.
11. Create "water banks" to allow trading of water rights. (This was suggested for the Upper Snake).
12. Crop changes to drought tolerant species.
13. Research and development of new crop types.
14. Transfer of water rights (regulators buy water rights; example given was Bureau of Reclamation).
15. Build small off-stream storage to meet local demand.
16. Negotiate for the use of increased Canadian storage.
17. Increase forecast ability (even an accurate 2-week look ahead was seen to be significant).

This is a considerable array of potential policy options to be grouped, ranked in order of priority, and evaluated. The one we shall evaluate first is creating water markets in order to increase efficiency of use.

We note in passing that the problems we have found in the management of water resources in the PNW are not unique to this region and that many of the regional deficiencies in institutional design are echoed at the Federal level. Rogers (1993), for example, characterizes the current federal system as being incoherent, producing incoherent policy characterized by:

a) too many agencies, committees, and interest groups with legitimate concerns; effective coordination difficult, if not impossible.
b) policies made in ad hoc, decentralized manner.
c) absence of water markets on large scale, except where scarcity forces states to face up to problem, e.g., California drought, 1987-1992.
d) large costs of maintaining current federal water policy, but expenditures not balanced with revenues.
e) large information gaps regarding ground water supplies combined with confusion about water rights.
f) general failure of river basin management---conflicts with land ownership and jurisdictional patterns.

Since the Federal/State/Regional systems are coupled in different ways "on the ground," change at regional levels will not be complete without corresponding change at the Federal level. It is our view that one can attempt to harmonize such change in two steps as follows:

1. Within the Executive Branch, create an interagency panel to harmonize Federal policy based on the two overriding policy objectives; then initiate a dialog with states on a regional basis; and seek to move agreed upon issues through the Congress as necessary. But realize that there is plenty of leeway within Federal and State law for harmonized action based on existing regulatory authority.
2. Facilitate Federal and State regional planning to respond to climate variability and change and deliberately connect agreed upon policies and procedures to implementation channels with declared accountability.

Existing and Potential Planning Adaptation and Mitigation Strategies vis-à-vis Climate Variability and Change

The fact is that there do not yet exist explicit policies in the region to respond to either current climate variability and future climate change, except for the single case of flood controls. The data show that only a very small group of agencies, all of them in the field of water resources management, including hydropower, have the technical capacity to consume, understand, and respond intelligently to probabilistic climate forecasts. These include the U.S. Army Corps of Engineers, the NOAA Northwest Regional River Forecast Center, the Bonneville Power Administration, Seattle City Light, Water Resources Division of Seattle Public Utility, National Resource Conservation Service, Bureau of Reclamation, Washington Dept. of Ecology, Oregon Climate Services, Northwest Power Planning Council, Washington Dept. of Fish and Wildlife. Consequently, climate forecasts are not now the path to policy design.

We have shown (Callahan 1997) that climate variability has played a role in the past in shaping the haphazard structure of the present management system. Historically, there were four occasions on which climate variability has clearly caused major shifts in policy. These are:

1. the 1870's-1880's when severely cold winters devastated the cattle industry on the Columbia Plateau and induced a shift from grazing to agriculture;
2. in the early twentieth century, when declining precipitation brought with it the large-scale irrigation of the Columbia Plateau;
3. in 1948 when severe flooding resulted in the Columbia Basin Project and a proliferation of dams; and
4. in the 1970's when a series of droughts caused significant power shortages highlighting the need for increased reservoir capacity in Canada.

Note that at least in the twentieth century, the drought periods are associated with positive PDOs and the flood period with a negative PDO. The initial policy response moved from one naturally unsustainable occupation (cattle ranching/grazing) to another (agriculture) requiring large-scale diversions of Columbia Water resources. Flooding, in turn, produced dams for flood control and hydropower, but their proliferation had seriously and permanently adverse effects on the region's salmonid resources. Note, too, that these policies were formulated and implemented without any understanding of the basic causal connections between climate variability and the impacts experienced. Systems were created which buffered society against climate variability but at the same time, they increased vulnerability elsewhere and exacted a harsh price on the region's biogeochemical systems. Much greater understanding of the dynamics of regional climate variability and the impacts they generate can now underlie the design of policies for the twenty-first century.

References

Broecker, W.S., 1987. "Unpleasant Surprises in the Greenhouse?" Nature, Vol. 328, pp. 123-126.

Broecker, Wallace S., 1997. "Thermohaline Circulation, The Achilles Heel of our Climate System: Will Man-Made CO_2 Upset the Current Balance?" Science, Vol. 278 (28 November), pp. 1582-1588.

Callahan, Bridget Mae, 1997. The Potential of Climate Forecasts for Water Resource Management in the Columbia Basin, MMA Thesis, School of Marine Affairs, University of Washington, (June), 142 pp.

Callahan, Bridget, Edward Miles, and David Fluharty, 1997. "Policy Implications of Climate Forecasts for Water Resources Management in the Columbia Basin," Paper presented to the American Meteorological Society, 10th Conference on Applied Climatology, Reno, NV, October 20-23, 1997.

Canning, D.J., 1998. Personal Communication.

Cayan, Dan, Kelly Redmond, and Larry Riddle, 1998. "Accentuation of ENSO effects on extreme hydrologic events over the western United States." Submitted to *Journal of Climate*, in review.

Dell'Arciprete, O. Patricia, David L. Peterson, Robert C. Francis, and Nathan Mantua, 1998. "Climate Reconstruction Through Tree Growth Indices." Paper prepared for the Year 3 Progress Report (July 1997-June 1998), JISAO/SMA Climate Impacts Group, University of Washington.

Garfin, Gregg M. And Malcom K. Hughes, 1996. "Eastern Oregon Divisional Precipitation and Palmer Drought Severity Index from Tree Rings," Laboratory of Tree-Ring Research, University of Arizona, Tucson, AZ, 85721; USDA Forest Service Cooperative Agreement PNW 90-174.

Gray, Kristyn and Alan Hamlet, 1998. "Extended Droughts Affecting Pacific Northwest Water Resources Systems," unpublished manuscript, JISAO/SMA Climate Impacts Group, Oct. 22.

Gu, D. And S.G.H. Philander, 1997. "Interdecadal Climate Fluctuations that Depend on Exchanges Between the Tropics and Extratropics," *Science*, Vol. 275 (7 February, 1997), pp. 805-810.

Guilderson, Thomas P. And Daniel P. Schrag, 1998. "Abrupt Shift in Subsurface Temperatures in the Tropical Pacific Associated with Changes in El Niño," *Science*, Vol. 281 (10 July), pp. 240-243.

Hamlet, Alan, 1998. "Effects to Columbia Basin Water Resources Associated with Climate Variability and Operating System Design," unpub. MS., JISAO/SMA Climate Impacts Group, University of Washington, April 15 revision.

Hamlet, A., D.P. Lettenmaier, and B. Nijssen, 1997. "Effects of Climate Shift on Water Resources Objectives in the Columbia Basin." JISAO Climate Variability, Impacts, and Response Strategies group Report for the July 1997 Pacific Northwest Regional Climate Change Workshop.

Hare, S.R., N.J. Mantua, and R.C. Francis, 1998. "Inverse Production Regimes: Alaskan and West Coast Salmon," in press.

Illahee. 1995. Journal for the Northwest Environment, Vol. II, No. 1 & 2 (Spring/Summer).

Intergovernmental Panel on Climate Change (IPCC), 1995. *Climate Change 1995: The Science of Climate Change: Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change.* J.T. Houghton, L.G. Meira Filho, B.A. Callader, N. Harris, A. Kattenberg and K. Maskell, eds., (New York: Cambridge University Press), Vol. I.

----, 1995. Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses: Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change. R.T. Watson, M.C. Zinyowera, R.M. Moss, eds., (New York: Cambridge University Press), Vol. II.

Johnson, Ralph W. and Rachel Paschal. 1995. "The Limits of Prior Appropriation," Illahee, Vol. II, Nos. 1 and 2 (Spring-Summer), pp. 40-50.

Johnson, Zoë, Elizabeth Arden, Douglas Canning, and Marc Hershman. 1998. "Sensitivity of the Coastal Management System in the Pacific Northwest to the Incorporation of Climate Forecasts and Long Range Climate Projections," paper prepared for the JISAO/SMA Climate Impacts Group Year 3 (1997-1998) Progress Report.

Kaczmarek, Z. et al., 1995. "Water Resources Management." Chapter 14 in: *Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses.* Intergovernmental Panel on Climate Change (IPCC), R.T. Watson, M.C. Zinyowera, R.M. Moss, eds., (New York: Cambridge University Press), pp. 469-485.

Laird, Kathleen R., Sherilyn C. Fritz, Kirk A. Maasch, and Brian F. Cumming, 1996. "Greater Drought Intensity and Frequency before AD 1200 in the Northern Great Plains, USA," Nature, Vol. 384 (12 December), pp. 552-554.

Lettenmaier, Dennis P., Kenneth L. Brettmann, Lance W. Vail, Steven B. Yabusaki, and Michael J. Scott. 1992. "Sensitivity of Pacific Northwest Water Resources to Global Warming," The Northwest Environmental Journal, Vol. 8, pp. 265-283.

Mantua, N.J., S.R. Hare, Y. Zhang, J.M. Wallace, and R.C. Francis, 1997. "A Pacific Interdecadal Climate Oscillation with Impacts on Salmon Production," *Bulletin of the American Meteorological Society*, Vol. 78, pp. 1069-1079.

Northwest Power Planning Council (NPPC). 1996. Personal Communication.

Office of Technology Assessment, U.S. Congress, 1993. Preparing for an Uncertain Climate, Vol. I, (Washington, D.C.: Government Printing Office), Chapter 5, pp. 209-274.

Pacific Northwest Waterways Association (PNWA). 1996. Personal Communication.

Rogers, Peter, 1996. America's Water: Federal Roles and Responsibilities, (Cambridge, MA and London: The MIT Press).

Seattle City Light, 1996. Interview with Mike Sinowitz, Power Production Manager.

Seattle Post-Intelligencer, July 17, 1996. Rob Taylor. "State Control over Water Strengthened," p. A1:5.

Seattle Post-Intelligencer, July 20, 1996. Jack Hopkins. "State Can Limit Access to Ground Water," Snover, Amy, Edward Miles, and Blair Henry. 1998. OSTP/USGCRP Regional Workshop on the Impacts of Global Climate Change on the Pacific Northwest: Final Report, NOAA Climate and Global Change Program, Special Report No.11, March.

White, Richard. 1995. The Organic Machine, (New York: Hill and Wang).