AN EVALUATION OF RESEARCH PROGRAMS AT THE CENTRAL SIERRA SNOW LABORATORY, 1945 — 1964

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ABSTRACT

Several public agencies took part in one or another of several cooperative programs investigating problems of the snow landscapes of the Sierra, and submitted their own problems of design and reservoir operation, river forecasting, and water and sediment yields. These problems were organized into a research program essentially centered on the fact that a snow landscape is the arena of interaction between water and energy; so the fluxes in these two physical budgets outlined our task. Of the three field basins active in the Cooperative Snow Investigations, the Central Sierra Snow Laboratory (CSSL) had the most detailed field observations; and in the later Snow Management program (FS), CSSL was the site of half of the research projects in the Sierra snow zone; it was the basin with which I grew most familiar.

Field observations and data analyses emphasized heat supply, characteristics of the surface of the snow, water transmission through the deeper layers, and stream flow; techniques for hydrograph reconstitution for Castle Creek were validated in operational basins like the Yuba and Kootenai Rivers. In the second program at CSSL, detailed measurements of the forest environment of each snow course gave data for analyzing the separate effects of trees on shortwave radiation, longwave radiation, shelter, and wind transport.

It is interesting that the intellectual curiosity of a university professor ninety years ago led to research that produced notable scientific findings about snow cover, and to physically sound operational techniques for design floods, flood forecasting, and managing the public domain. I feel privileged to have been a part of these major research programs in the physics of this complex mountain landscape, and now appreciate the invitation to evaluate these programs from the viewpoint of my subsequent scientific career.

A. POINT OF VIEW ABOUT CSSL

I present here a subjective, almost impressionistic view, as seen from one generation later, of what I consider to have been two extremely successful Federal research investigations that made use of the same small drainage basin (hereinafter CSSL) in the crest region of the central Sierra Nevada. This evaluation, or post-mortem, embodies ideas that have since come to me about physically-based environmental research in a well-equipped field area; but it is also to be seen in the broad context of my subsequent career, less analytical and more synthesizing, attempting to understand how the earth's surface works. How do soil, vegetation cover, snow cover and other surfaces process the inputs of mass, especially water, and of energy in many forms that come to them unbidden? This has been a fundamental question in science since the 1880s.

I had worked with water and energy budgets in military situations before 1946, and so, on transferring to the Cooperative Snow Investigations of the Corps of Engineers and Weather Bureau (SI) I was assigned to develop a comprehensive research plan. This research was to be done to support such basic aims as the methods to determine design floods, especially the probable maximum, to operate reservoirs, and to forecast river flows from melting snow and from rain-on-snow events. This task required taking note of such energy- and water-budget questions as snow-surface albedo, terrain effects on water equivalent in the accumulation and melting seasons, and intensities of the four fluxes of radiant energy in the environment. The subsequent Forest Service/State of California program (FS) also centered on these budgets to support research seeking techniques

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for practical applications of research results, but with special attention to the detailed influences of forest on each flux of water, like its interception of falling snow, and on each energy flux.

Both programs provided me an opportunity and an obligation, with good field observations, to examine these budget questions in the real world, as it is sampled in CSSL. An interlude in research administration did not interrupt this thinking about budget analyses, which I applied to the Greenland ice cap and to publishing a volume about regional climatology from my dissertation under John Leighly (Volume 11, University of California Publications in Geography, 1955) that turned out to have a crucial value in my career.

Such an impressionistic view is not in any way a history of work at CSSl, with dates and footnotes and other historiographical apparatus. This history remains to be written, perhaps by a man or woman presently a student of mountain snow. However, I hope that the opinions laid out here might give a helpful perspective on how these two Federal programs came to be so successful and to give the government much more than its money's worth.

B. THE AIMS OF THE COOPERATING AGENCIES

Each agency taking part in one or another cooperative investigation of the Sierra snow cover in the period from 1945 to 1964 perceived its own particular needs for certain kinds of information. Most of these needs derived from agency missions, including the responsibility for river forecasting, for such river structures as dams, reservoirs and levees, for water and erosion on the public domain, and for basic measurements of precipitation and other elements of the climate. In addition, individual field offices of an agency might have their own agenda. For example, several offices of the Corps of Engineers submitted questions involving hydrology of dam and reservoir design in the districts, probable maximum flows for spillway design, and operating rules for managing flood-control works and reservoir storage. The Sacramento District, as a case, had to deal with snowmelt floods, rain floods, and difficult rain-on-snow events, both for an active flood-control project (which figures, along with the crest region, in George Stewart's great 1941 novel, "Storm"), for designing reservoirs on seven large rivers, and the balancing the operation of reservoirs among conflicting demands for water in winter, spring, and summer. Somewhat different agendas came from district offices in the Northwest. The Weather Bureau needed still other kinds of information about snow on large drainage basins.

The specific needs of these and other agencies, included those for military applications for SIPRE (another cooperator), in mountain hydrology by the Geological Survey, and in a later period by the Forest Service and State of California. Together these requirements encompass a good deal more than the snow surveys long active in the western mountains. The additional needs include thermal quality and water-transmission and storage capacity of snow, the areal extent of a snow cover, effects of storm weather effects on meltwater generation and runoff, snowfall in extensive upland areas with few precipitation gages or with gages of known deficiencies, spatial variations of snow cover and weather elements as they are affected by topography and forest, sampling in rugged terrain with patchy forest, and potential changes as forest openings or gaps are created by fire or logging.

Some of these knowledge requirements were broadly shared among several cooperators, while others were of mainly local interest. All agencies felt responsible for training their hydrologists and other professionals in whatever new data and techniques might develop during an investigation, and also to be told of negative results of a particular research project, as the Seattle District emphasized. The outcome was a shifting array of 'cooperative' programs as time went on, and shifting observational programs in the three laboratory basins and especially at CSSL.

C. CSSL INSTRUMENTATION AND OBSERVATIONS

Engineer and Weather Bureau Program (SI)

A little like a legacy of a short cooperative program at Soda Springs between the Weather Bureau and the University of Nevada (not the first of such brief cooperations with Dr. Church since 1906), Dr. Robert Gerdel, an all-around natural scientist, apparently was available, when the SI was deciding to go to field research rather than plot studies. It chose the small drainage basin of then Castle Creek. Probably the choice was also affected by the need for winter access by a plowed highway, U.S. 40 (and by rail, as in the 1950 flood). Gerdel was able to start instrument procurement almost at once.

Laboratory facilities, especially a flume and headquarters structure, were built by the Sacramento District - sound structures that were still in service in 1964. With Gerdel's help, advanced instrumentation was acquired. Mass-budget research called for measurements not only of the snow itself but also its content of liquid water, shielded and improved precipitation gages like those tested at Soda Springs, soil-moisture blocks, soil and snow temperature equipment, and the Parshall flume, for high runoff, with a V-notch weir for smaller flows. (My first contact with the laboratory was preceded, as Gerdel and I walked up from the highway, by meeting a picturesque stream of profanity as Ash Codd struggled in icy water with a jammed weir gate.)

A geomorphological analysis of basin topography from a 1:12,000 map prepared by the Forest Service and a geological survey of the basin (unfortunately only in part on public land), made possible statistical stratification of sampling sites for gages, weather stations, and snow courses so that observations would provide the most adequate representation of the 10 sq km area. Additional analyses were done on the necessary number of sampling points at each snow course, which varied from three to five up to the customary 15 to 20 points along a line, and computation of standard deviations of measured water equivalents served to check the adequacy of this micro-scale sampling. Precipitation gage deficiencies, well known in hydrology, had been studied in the Nevada program, with various shielding devices, and some of this work continued in the SI program (Wilson, Mon. Weather Rev. 82, 1954).

Wide interest in rain-on-snow events led to building a small, solid-bottom lysimeter on a ledge near Headquarters, which served in several natural floods and sometimes received sprinkling by water from nearby Castle Creek. Dye studies and dielectric measurements were made by Gerdel of paths of rainwater or meltwater through the two to three-meter deep snowpack, as well as the structure of snow crystals after heavy rain, more or less to check the old notion that snow is just a big sponge. Occasional deep pit studies revealed the stratified structure of the snowpack, and suggested that each stratum still, after months, remained marked by the conditions of storm temperature and wind that deposited it earlier in the season. These strata often preserved their individuality when each one was exposed at the surface in the spring ablation period, as shown in significant shifts in its albedo, an interesting case of natural memory (Miller, SI Res. Note 1950). Of course, the spring snowpack as a whole is a memory of winter storms, embodied in the several-months delay between deposition of snow and generation of meltwater that makes snow surveying so successful in forecasting summer stream flow.

Vapor pressure measurements revealed the unexpected fact that above a snow surface at 0°C and vapor pressure 6.1 mb, the local air often displayed a vapor pressure of 10 to 15 mb, in nonadvective weather. A similar excess of air temperature above 0°C was also unexpected, contrary to statements in meteorology textbooks since the 1870s.

Since the melting of ice or snow is a change in physical state that involves latent energy, the energetics of snow and snow environments were given close attention when CSSL was instrumented. Paired pyranometers for incoming and reflected solar radiation, one of few such stations in the U.S., provided good hourly observations of albedo of the snow surface, which is one of the most important characteristics, as emphasized by Bottorf, of the snowpack. For several years, our data on snow albedo were the best in the world, except perhaps at the main station of the Soviet hydrometerological system under Budyko, which paid a lot of attention to radiant energy. (Comparison with Russian material was possible only after Budyko's program became known by his visit to a WMO meeting in Washington in 1957.) Comparison of our data with shorter runs in the Alps and Scandinavia showed generally lower figures, which can be ascribed to changes in the snow surface at CSSL - grain-size, length of daily wetness, - during the long anticyclonic weathering periods after snowstorms (CS-171 Tech. Bul. 6, 1950).

In later years of the SI program, we borrowed a longwave radiation instrument developed by Professor Fred Brooks, a radiation meteorologist at the University of California at Davis, who had studied longwave radiation for years in connection with frost damage. This instrument, a flat-plate radiometer, actually measured longwave plus shortwave; shortwave measurements from a pyranometer were subtracted to arrive at values of incoming longwave from atmosphere, clouds, and in forest sites, from tree canopy. As is well known, this flux is often the largest component of the energy budget. A small flux at open-sky sites at night often allowed crusting of the snow to a depth of 8 to 10 cm, when at the same time snow under adjacent forest remained completely uncrusted, and presented a hazard in cross-country skiing.

A set of thermometers to a height of 18 m above the snow at Headquarters showed solar heating of tree crowns, even in this relatively open second-growth lodgepole pine forest (CW-171, Tech. Bul. 12, 1950), and suggest the source of the anomalous air temperature and humidity noted earlier. At night they showed the shallowness of cold-air drainage, as the down-valley wind. Valley inversions mapped from temperatures at the six field stations showed a different aspect of cold-air drainage especially in anticyclonic circulation aloft. Micrometeorological measurements were also made at four masts in the Lower Meadow in the SIPRE—Engineer program.

Occasional short-run measurements are reported in the annual logs or technical reports and include snow temperatures at various depths in the pack, liquid-water content by calorimeter, hourly drainage from a slat-floor lysimeter in the Lower Meadow, and areal extent of snow cover during the melting season (Depletion of snow cover and runoff relations, Miller Res. Note 16, 1953). Maps of the upper-air flow were another information source (Res. Note 15).

All measurements and observations were sent weekly to be processed in San Francisco, logged in, given quality inspection, tabulated, and summarized. Most chart data were not digitized and needed much transcription time, which provided for a second quality checking. Several annual reports present time studies for these lengthy office operations and quality control. For a time, early publication of the hydrometeorological logs was possible, but after they fell behind a major catch-up effort by graduate students from the University of California was needed toward the end of the SI program to get logs published for all three field stations.

Cooperative Snow Management Research (FS)

Scientists and technicians who work at a research site are familiar with the quality of its measurements, and are also aware that in a fluctuating climate the value of an observational record increases as more years accrue. So they hope that after they leave others might come in to use the site and its data sets, and extend the record. Even if the former records might have already served one purpose, they might yet prove to be a key to another problem, previously unseen. So it gratified me that heavy use continued to be made of what I knew to be good data at CSSL, aided by the Engineers' policy making field data widely available as early as possible, in the form of hydrometeorological logs. While most logs included no analytical material, the first one to be published, for the water year 1945-46 (SI Tech. Rep. 5) did contain analytical findings of many projects, which were presented to the AGU in 1948 though journal publication was hung up for unknown reasons until they were submitted elsewhere (Bul., AMS, 1950). Lab data were further made usable by a five-year summary for 1945-1950 (Tech. Rep. 6-4), with basin maps, inventories of observations, and a condensed outline of the analytical programs. These published data have been used in classes in forestry and soils at the University of California and in several theses and dissertations, including my own, which, with NSF support examined the time-hallowed theory that snow cover produces a cold climate. (This theory does not apply to the Sierra, and explaining why it does not required an energy analysis of upper-air circulation, solar radiation, forest canopy, and snow cover.)

A major use of CSSL data and observation sites began when Ted Colman, before his untimely death, initiated in 1955 a study of the entire snow zone, with help from the State California (to me at least, an invisible cooperator). This program, FS, was launched by using the old data sets on water equivalents at snow courses in CSSL to explore the effects of forest on snow accumulation and melting. Course descriptions were supplemented by silvicultural data on species, age, heights, and canopy closure at each snow course (Anderson, Rice and West, WSC Proceedings, 1958). Detailed maps of each course and several measures of canopy closure overhead anticipated recent ecological studies of forest gaps.

Another supplement that enhanced the analytical value of the old SI records was a map of soils and vegetation of the basin. This map showed a mosaic pattern of about 300 entities, each one of which is homogenous within itself but contrasts with neighboring entities. It can be called a patch or an ecosystem in the hierarchy of current landscape ecology. These 300 ecosystems cover the twenty topographic facets identified in the SI program, each of which exhibited a certain uniformity in snow cover. As a whole, the 300 ecosystems make up the landscape mosaic we see from a high point. Terrain inventories of the whole Sierra snow zone by Richards at the start of the FS program confirm that CSSL characteristics suitably represent typical characteristics of the whole snow zone.

The new FS program inherited the headquarters building constructed years before by the Sacramento District, restored the flume, and resumed or expanded observations of weather and radiation fluxes. Provision was made to measure sediment flows, and selected sites for measuring soil moisture in the quantities made possible by neutron equipment.

The network of snow courses from SI days was expanded from time to time in order to sample a greater range of forest environments. Additional courses were operated on occasion to sample a variety of cutting patterns, such as strip cuts of different orientations and widths, block cutting, and so on, in nearby parts of the crest region. After the Donner Ridge fire in 1960, several snow courses and erosion stations were laid out to sample different recovery treatments of the burn. Also outside CSSL but within a few miles, stations were set up in several small subbasins of Onion Creek.

D. ANALYSES OF CSSL OBSERVATIONS AND DEVELOPMENT OF TECHNIQUES

Engineer and Weather Bureau program (SI)

The initial research needs of the Engineer districts, Washington office, and Weather Bureau were expressed in a conference in 1945, with such consultants as H.U. Sverdrup and Jakob Bjerknes, and were then organized into a five-part classified research outline (Tech. Rep. 6, 1947). Part 1 was seasonal totals and volumes. Part 2, time rates of water and energy fluxes, was the largest part of the program, identifying projects in heat transfer rates, rates of melting and runoff, and so on. Part 3 dealt with spatial or areal distributions of energy transfers and snow, and especially of the snow cover itself in an environment of rough topography and patchy forest that is so different from the locales of the pioneering glaciological work in Scandinavia. The SI and FS programs were, naturally, modifications of this prior work by men like Sverdrup and Wallén (who visited CSSL in 1947, to our great benefit), to accommodate the different environment of the western mountains. It might be mentioned that other visitors, steered West by the Office, Chief of Engineers, were M. de Quervain (who outskied all the locals) and H. Bader (author of the classic "Der Schnee und seine Metamorphose") from the Swiss research Institute on Snow and Avalanches in Davos. They also were helpful to field and analysis people here, who also used the extensive holdings in the Forestry, Engineering, Geography, Biosciences, and Doe libraries at the University of California-Berkeley, and often talked with faculty members at Berkeley, Davis, and Los Angeles.

Part 4, one of the facilitating parts of the program, dealt with methods generalized and simplified from rigorous analyses of physical processes in energetics and water balances. These included also terrain analyses in numerical terms permitting transfer from CSSL or other basins to the large operational basins of practical interest. Part 5 was an on-going appraisal of station exposures and observational procedures, with quality control of all observational data sets.

Annual conferences of hydrologists and meteorologists from Engineer districts, like Francis Murphy and Meredith Thoms from Seattle, and the national level, like Frank Snyder and David Hullinghorst, maintained continuous liaison between the San Francisco people and operational realities, and equally important, gave our work essential support at budget times. Relations with Washington were as good and helpful as I have seen them in any other Federal program. This was partly due to the scientific respect due Frank Snyder for his accomplishments in hydrology, and his helpful role as a broker interchanging snow-related information among the field offices he regularly visited.

At a critical time in the life of the SI program, a program of the Office, Chief of Engineers project was set up in San Francisco to by-pass roadblocks in publishing research results, encourage methods of hydrograph reconstitution, and bring field hydrologists, especially from the Northwest, to work with analysts in San Francisco. Reconstitutions were done first for Castle Creek (CW-171 Technical Bulletins 8, 9, and 10 in 1950), and then for large rivers like the Boise and the Kootenai, and for Pine Flat Reservoir inflows. S.E. Rantz later applied these methods to the North Yuba River in a U.S.G.S. Water-Supply Paper (1779-R, 1964). Many of the two dozen or so field hydrologists who came to work for three weeks, on their home or any other problem they chose, often made use of CSSL observations as good data sets.

Previously-done analyses that found a publisher in the CW-171 Project were included methods for estimating incoming solar energy where pyranometers were lacking, the micrometeorology of snow in forest, with the help of Professor Kittredge at U.C., with some information on possible convective heat transfers, the unusually low albedo and its decrease in periods of rapid weathering of the snow surface after storms (due only in part to the melting out of bark fragments and other debris in the snow), all from the excellent CSSL observations (Tech. Bul. 6). Other reports described Hullinghorst's unit-hydrograph and S-curve techniques. To me, a person whose training in hydrology was entirely on the job in working with colleagues like Rantz and Hullinghorst, the ability to derive hourly flows in 1946 and 1947 solely from weather data was highly impressive!

In addition to energy and water-balance work reported in several of the SI Research Notes (an unnumbered series) there were included methods to estimate both shortwave and longwave radiation in relation to environmental conditions. Two of this series (1951 and 1953) reported on influences of terrain on snow water equivalent, making use of quantitative geomorphological data on slope steepness, orientation, shape, ventilation and other dimensions identified by R.E. Horton and French geomorphologists. Some of these multiple regressions went far beyond the then existing capabilities of Friden desk calculators and used IBM facilities to do things that the local IBM people told us were impossible.

Field studies were made by the Snow, Ice and Permafrost Research Establishment (SIPRE, now CRREL, a Department of Defense agency) at the Lower Meadow, which afforded a more open site than Headquarters but required rebuilding of a mile of road up into the basin. (Lower Meadow is at present a parking lot for a ski resort.) Analyses included a weather summary of five years of observations at Station #5 and detailed account of weather at the Meadow in 1950-1951 by Patton, and an analysis of snow density. Some of these foreshadowed later snow pit measurements and readings of meltwater drainage from a slat-floor lysimeter. Standard turbulence indexes were computed from measurements at four masts crossing the meadow.

The somewhat confusing existence of several report series, including the hydrometeorological logs that occasionally included analytical results, and the CW-171 and SIPRE series, which derived from the separate cooperators in the program, is ameliorated by the fact that many analytical results are summarized in the monumental "Snow Hydrology" (Snyder, Bill Bottorf, and Dave Rockwood, editors, 1956) that was published after the nominal SI program moved to Portland in 1953. Its materials are in large part based on CSSL data, since the Upper Columbia lab had less intensive instrumentation and the Willamette lab had a shorter history. This volume is still being cited forty years or more after CSSL closed in 1953 as an SI facility.

In my opinion, however, neither "Snow Hydrology" nor the reports in the series above-mentioned take the place of reviewed papers in professional journals, which, like those in the WSC Proceedings, are written by the investigator himself and exposed to public inspection over his own name. This opinion appears in a discussion paper in the American Society of Civil Engineers Journal of the Hydraulics Division in 1959 (85, Hy 8:109-117) which sums up the water and energy-budget aspects of the SI and appends a long bibliography that might be a useful guide to those interested in CSSL or the whole analytical program.

Forest Service Snow Management Program (FS)

As members of the Western Snow Conference know, analyses made in the Forest Service/California snow management program (FS) were reported in the professional literature more fully than those done by SI workers; the FS program contributed every year to WSC meetings as well as to other societies. Being concerned with yields of meltwater and sediment from landscapes of the entire west-side Sierra snow zone, FS spread its research sites, leaving only about half of the studies to be done at CSSL. Still, CSSL was a good place to examine how forest of different kinds and dimensions influences wind and snow accumulation (especially in southwest winds, as Court (1957 Proceedings) showed), and in quite different ways influences radiation fluxes and snow melting.

The FS analytical program included four groups of studies. One group inventoried the terrain of the whole snow zone, including CSSL forest, soil and vegetation; a second group dealt with weather and radiation, mostly at CSSL; the third group sought to develop methods to increase water yield and control sediment through forest cutting practices; and the fourth tested these methods in small drainage basin, usually in the traditional pairing of stream and rain gages.

A simplistic pairing of input and output treats the basin as an unknowable 'black box', but can be made more rigorous by investigating the specific dimensions of forest openings. Each dimension individually affects separate transactions and transfers within the black box, with respect to influences of trees on falling snow (interception), and how forest and weather factors affect the disposal of intercepted snow, for example. Forest factors that affect generation of meltwater are the transmission of solar radiation through forest canopy (Muller), the emission of longwave radiative exchanges between forest canopy and snow on the forest floor, and the shelter effect of forest, especially in advective melting weather and in large rainstorms.

These analyses attempt to quantify Church's long-ago dictum that the ideal forest for snow country has the pattern of a honeycomb. Parallel research has been done in flat landscapes crossed by shelterbelts common in the North American Great Plains and southern Russia. In mountain forests, however, these management techniques encounter the complicated aerodynamics of openings of different shapes, orientations, depths, and widths, all of which affect size and number of atmospheric eddies that transport light snowflakes.

In an attempt to generalize this complexity into a workable generalization about interception of snow, we studied some 110 field studies, some of multi-year length. Disappointingly, we found that none of these long studies included all three factors necessary for a physical solution: i) storm wind and temperature; ii) quantitative information on canopy architecture (not then studied as much as it is now); iii) the changing loading of snow on tree crowns, which should tell us, as in some Japanese studies, the rate at which the snow load builds up during a storm and later leaves the crowns by blowing out of them, sliding off, melting in place, or, rarely, evaporating into cold or humid air. Unless all three factors are known, no practical use can be made of these hundred-odd investigations; this field work, sadly, was done in vain. West found little evaporation of snow on the ground except in a period of easterly, Chinook-like air flow.

Better results, fortunately, came from analyzing basin topography and its effects on snow accumulation and melting. This work continued the multiple regressions of the earlier SI program, and improved on them by using better information on the forest environment of each snow course.

"Loss" from basin water budgets in summer is better defined than it is in winter, when little snow in the snowpack or on forest canopy evaporates (Proceedings 1962; Res. Note PSW 19). While some evaporation occurs from meltwater pools and wetted soil around snow patches of late spring, most of the evapotranspiration in the annual cycle represents summer transpiration by deep-rooted trees and shrubs in the high-energy months. Kenneth Knoerr's 300 neutron-probe points in forty or so sites showed significant differences among forest types and soils, and, when averaged over all of CSSL excluding bare rock averaged about 250 mm. Knoerr's dissertation (1960) under W.E. Reifsnyder, a forest meteorologist at Yale with extensive experience in California, other mountains of the western U.S., and the Alps, demonstrated that, soil-moisture levels being equal, evapotranspiration is a function of day length and saturation vapor-pressure deficit. A later M.S. thesis showed transpiration changes in sites of different lengths of time since logging (Ziemer, 1963).

During this second period of research with CSSL materials, Castle Creek basin was destroyed as a hydrologic research site by logging operations that put landings in stream beds and roads that eroded rapidly; soon after, by careless dirt movement and even invasion of the channel of Castle Creek (which soon fought back) during construction of the interstate road. The FS made timely arrangements for measuring suspended sediment in the stream, and changes in channel deposits, with some data on erosion, but for all practical purposes a unique site to study snow runoff with the advantage of a long record of such studies has disappeared from the face of the earth. Subsequent work around Headquarters and in the Onion Creek basins is beyond the scope of this evaluation.

E. CONCLUSION

The two periods in which I took part in research on mountain snow cover prior to 1964 I now evaluate as having good scientific and operational outcomes, as well as aiding my subsequent scientific work. For example, we now have better information on snow-surface albedo and on the disposition of intercepted snow. We have better techniques for determining potential river behavior, for managing forested landscapes, and for applying the powerful budgets of water and energy to develop hydrographs from purely atmospheric data, not just in little Castle Creek but in large rivers like the North Yuba and the Kootenai. We can now supply estimates of the radiation fluxes as parts of the thermal energy that alone can transform a quiescent snowy landscape into meltwater floods, and can apply upper-air data more confidently to phenomena of hydrology, forestry or engineering down at the earth's surface.

The mythical separation of theoretical versus applied science never was apparent to me in the Sierra; I wonder if it exists anywhere in the real world. Rather, I found that when one seeks a practical algorithm for a process in the environment like streamflow or the disposition of intercepted snow, it is absolutely vital to first make a physical analysis. The objectives sought in operating and design techniques were attained only by making physical analyses of energy and water exchanges between the snow cover and its atmospheric and terrestrial environment, based on good field measurement as at CSSL.

Many of my present interests can be traced to roots in my experience with CSSL, which I see as a cradle of much good scientific and applied knowledge. High-quality data from this well-instrumented field area that one could ski or walk over made possible sound analyses that supported many useful techniques and procedures. For me, personally, in talking and working with such colleagues as Rantz, Gerdel, Bottorf, Anderson, and Court, among many others, I learned a lot. I was lucky to receive the opportunities presented in these two periods.