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Water Balance and Regulation Alternative Analysis for Kajakai Reservoir using HEC-ResSim

Phase I and II Final Report

December 2007

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The purpose of this report is to provide updated information for long-term planning on the capacity of the Helmand and Arghandab Rivers and respective reservoirs, Kajakai and Dahla, to support irrigation needs in the Helmand Basin and power production at the Kajakai powerhouse. It also details a regulation alternative analysis that presents the benefits and drawbacks of different regulation strategies for Kajakai Reservoir. This analysis was sponsored by the United States Agency for International Development (USAID) and was performed by the HEC, which is part of the United States Army Corps of Engineers (USACE).

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Introduction

This report provides a consolidated account of the work performed by the Hydrologic Engineering Center (HEC) during Phase I and Phase II of the Helmand Valley Water Management Plan study. This report accommodates new data and provides updated results based on information gathered since the Phase I report was finalized. Phase I consisted of data gathering and validation, developing a reservoir simulation model of Kajakai Reservoir and completing a water budget analysis to illustrate the capacity of the Helmand Basin to provide water for irrigation, power supply, and International treaty requirements. The larger Phase II effort of the Helmand Valley Water Study consists of updating and expanding the HEC-ResSim model developed in Phase I, updating the water budget analysis, performing a probable maximum flood (PMF) review and analysis for Kajakai Reservoir, and developing a draft regulation manual for Kajakai Dam. Under Phase II, the reservoir simulation model of the Helmand basin was expanded to include the Arghandab River and Dam (Dahla), and demands were updated to reflect recently completed irrigation studies in the valley.

The purpose of this report is to provide updated information for long-term planning on the capacity of the Helmand and Arghandab Rivers and respective reservoirs, Kajakai and Dahla, to support irrigation needs in the Helmand Basin and power production at the Kajakai powerhouse. It also details a regulation alternative analysis that presents the benefits and drawbacks of different regulation strategies for Kajakai Reservoir. This analysis was sponsored by the United States Agency for International Development (USAID) and was performed by the HEC, which is part of the United States Army Corps of Engineers Institute for Water Resources (USACE).

This report supersedes the "Water Budget Analysis for Kajakai Reservoir using HEC-ResSim" report dated September 2005.

A goal of this analysis was to use the Hydrologic Engineering Center's Reservoir Simulation Program (HEC-ResSim) to recreate and update the water balance analysis of Kajakai Reservoir performed by Water and Power Consultancy Services (WAPCOS) in 1979, which they completed as part of a feasibility study on extending the Kajakai hydroelectric station. Another goal is to study and provide information on possible reservoir regulation alternatives at Kajakai reservoir.

HEC-ResSim is a planning and real-time decision-support tool for single and multi-reservoir system management. The HEC-ResSim software performs hydrologic routing and determines reservoir releases based on a rule curve approach plus user-specified operating rules to meet multi-purpose, seasonal, at-site and downstream operational goals, including: flood reduction, water supply, hydropower generation, and stream flow requirements.

The WAPCOS study looked at the feasibility of installing three 33.3 MW units to the power plant. Flow data for the Helmand River, spanning 1947 to 1974, were used to address the level of reliability of the reservoir to serve irrigation needs in the Helmand Valley and to evaluate the amount of power that could be generated from the Kajakai powerhouse. Details of the WAPCOS feasibility study are not well documented.

In addition to revisiting the WAPCOS feasibility study, as a part of this water balance analysis, flow records have been extended through 1980 to capture all the available data. A reservoir model for Kajakai (Helmand River) and Dahla (Arghandab River) was developed using HEC-ResSim. Using the reservoir model and the available flow data, this analysis makes assumptions concerning hydrology, irrigation demands and power production, to roughly evaluate:

1. **Phase I -** The hydrologic feasibility and water supply benefits of operating Kajakai with and without the proposed spillway gates and with and without the additional hydropower capacity.

2. **Phase II -** Three different Kajakai Reservoir regulation alternatives, assuming the gates are installed, that focus on (1) Meeting full agricultural demand every year; (2) Modifying agricultural targets based on measured snow water equivalent in the Kajakai watershed; (3) Modifying agricultural targets based on measured snow water equivalent and making pre-releases to minimize peak flows downstream of Kajakai.

Kajakai Reservoir

Watershed

The Helmand River Valley, including all tributaries, drains approximately 160,000 km^2 or 31% of Afghanistan. The Helmand River accounts for 80% of the total Helmand basin runoff, and is estimated to have an average annual yield of 14,000 million m^3. The watershed begins in the Koh-I-Baba Range about 50 km west of Kabul. As illustrated in Figure 1, the Helmand River flows in a southwesterly direction for approximately 1,300 km towards the Afghan-Iran border where the Helmand branches out into the landlocked depression area of the Sistan wetlands.

The majority of the flow in the Helmand originates from the spring snow melt in the mountains of central Afghanistan. Flows into the Kajakai Reservoir begin increasing in March and peak in April at a rate of 500 m^3/s. Flows steadily decrease to a mean base flow of 50 m^3/s in July.

A major tributary of the Helmand is the Arghandab River. The Arghandab enters the Helmand approximately 130 km downstream of Kajakai. The rock fill Dahla dam is located on the Arghandab approximately 30 km northwest of Kandahar (Qandahar) and is used primarily for irrigation storage.

Figure 1. Map of Afghanistan.

Dam Features

The major water control structure along the Helmand River is Kajakai Dam. Kajakai Dam is a 90 m high earth and rock fill embankment dam, built in 1953. It is located about 100 km northwest of Kandahar and is used for irrigation storage and power production.

In 1975, a powerhouse was added to Kajakai Dam. It features two 16.5 MW units and space for a similar third unit, which when installed would provide the planned total of about 50 MW. The powerhouse foundation can be expanded to hold 2-4 additional units. Previous studies have suggested this expansion should consist of three 33.3 MW units, potentially adding another 100 MW of generating capacity.

The dam, which has an uncontrolled open channel spillway, was originally constructed during the early 1950s to provide flood control and irrigation benefits. Work on the planned spillway gates, new emergency spillway, and raising the dam crest commenced during the late 1970s, but construction activities ceased during the Russian occupation and these facilities were never completed. Consequently, the reservoir has never been impounded to its design level elevation of 1045 m.

The following items were constructed during the original construction of Kajakai Dam in the early 1950s:

- embankment dam with an original design crest level at elevation 1050 m;
- ungated open channel spillway with 100 m long weir in the spillway (crest level at elevation 1033.5 m);
- two unlined diversion tunnels;
- irrigation intake structure, located upstream of the dam's left abutment;
- three steel conduits for irrigation water supply in the outer or left diversion tunnel, which extend downstream from the concrete plug structure; and
- irrigation discharge structure, which includes three control valves.

After the initial construction of Kajakai Dam, the following facilities were added to allow for power generation:

- power intake structure and inclined power tunnel leading to the inner or right diversion tunnel;
- 3.6 m diameter steel penstock located within the inner or right power tunnel, extending from the new concrete plug to the powerhouse;
- three bay surface powerhouse;
- installation of turbines and generators in the outer two bays (Units 1 and 3); and
- foundation preparation for a powerhouse extension.

Planned facilities not yet constructed include:

- gated spillway with spillway crest raised to 1037.0 m;
- powerhouse extension including three 33.3 turbines; and
- new emergency spillway to account for modifications to existing spillway.

The HEC-ResSim model developed for this water budget and operational alterative assessment analysis requires a physical description of the reservoir, dam, power generation capabilities, and outlets. The physical description is supplied to the model through various relationships. Tables listing the relationships used for this analysis for both the existing and proposed state of Kajakai dam are contained in Appendix A. We collected the physical data for these dams from a variety of sources including old reports and Afghanistan Engineering District (AED) staff. All modeling efforts, including the physical parameters, were coordinated and verified with the United States Agency for International Development (USAID), AED, and their experts as much as possible.

Hydrology

The Helmand River drains a catchment of approximately 47,300 km^2 at Kajakai Reservoir. The average annual precipitation in the catchment is about 19.8 cm and the majority of the flows into the river are contributed by snow melt during the filling season from February to July (Dalu to Sartan).

Hard copies of historic reservoir storage levels and flow records at the gage directly downstream of Kajakai Reservoir (Below Kajakai) were obtained from the USACE Afghanistan Engineering District (AED) for the period of Oct 1947 through Mar 1980. The flow and storage values were available as monthly averages for the period of Oct 1947 through Sep 1960. For the period of 01 Oct 1960 through 31 March 1980, the values were available as daily averages. All storage and flow values were transferred into HEC's Data Storage System (HEC-DSS).

Net inflows into Kajakai Reservoir were computed using mass balance at Kajakai Reservoir from the equation:

$$Q_{in} = \Delta S + Q_{out}$$

Where:

Q_{in} is the net volume of inflow into the reservoir for a given time period,

Q_{out} is the volume of flow released from the reservoir for a given time period, and

ΔS = the change in storage from one time period to the next.

The outflow from Kajakai Reservoir was assumed to be equal to the recorded flow at the gage directly below Kajakai. The change in storage was computed directly from storage records obtained from AED. This technique accounts for losses from the reservoir due to evaporation and seepage, because those would be reflected in the change in storage from one period to the next.

Flow data were not available for any time prior to Sep 1947. However, net inflows into Kajakai Reservoir for the period from Oct 1946 through Sep 1947 were available in the WAPCOS report.

Since actual flow data for this period was not available elsewhere, we used the net inflow values directly from the WAPCOS report to fill in this time period.

HEC-ResSim operates on a time step no larger than one day. Therefore, after computing net inflows into Kajakai Reservoir, the average monthly inflows for the time period of Oct 1946 through Sep 1960 were transformed to average daily inflows. To do so, the average daily inflow (cms) for each day in a month was set equal to the average monthly inflow (cms) for that month. These were combined with the computed daily net inflows from 01 Oct 1960 through 31 Mar 1980 to produce a complete record of daily net inflows used in this analysis.

Monthly inflow data into Kajakai Reservoir were available in the WAPCOS report for the period of *water year* 1947 to 1974 (1326 to 1353). The water year begins on the 1st of October (Mirzan). So water year 1947 covers the period from 01 Oct 1946 to 30 Sep 1947. A comparison between average net monthly inflows into Kajakai Reservoir computed for this analysis versus the average net monthly inflows from the WAPCOS study is illustrated in Figure 2.

A comparison between annual net inflow *volumes* to Kajakai Reservoir computed for this analysis versus the annual net inflow *volumes* used in the 1979 WAPCOS report is illustrated in Table 1. The column labeled “Difference” in Table 1 was computed by subtracting the WAPCOS computed inflows from the HEC computed inflows.

Specifics of how net inflows into Kajakai Reservoir were computed are not detailed in the WAPCOS report. Therefore, it is difficult to assert why inflows computed for this analysis do not exactly match those computed for the WAPCOS study.

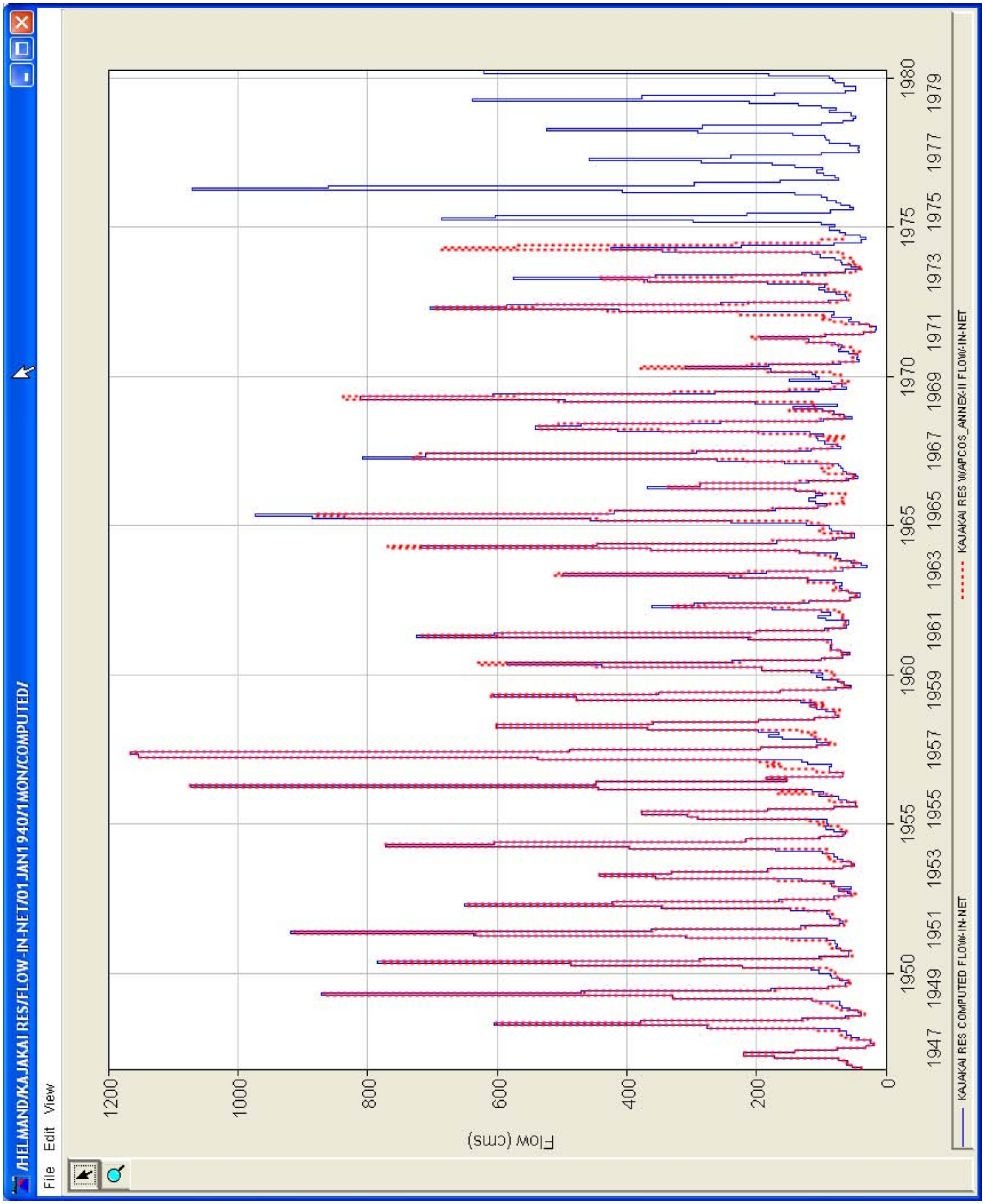

Figure 2. Average monthly net inflow (cms) into Kajakai Reservoir (HEC computed vs. WAPCOS).

Table 1. Annual net inflow volumes to Kajakai Reservoir by water year.

Water Year	HEC Computed (Mm^3)	WAPCOS (Mm^3)	Difference (Mm^3)
1947	2544	2544	0[1]
1948	4778	4898	-120
1949	6400	6503	-104
1950	6481	6193	288
1951	7607	7745	-138
1952	5933	5747	186
1953	4993	5163	-170
1954	7117	7016	101
1955	4670	4687	-16
1956	7554	7834	-279
1957	11167	11940	-773
1958	6816	6167	648
1959	6170	6093	78
1960	5697	5556	140
1961	6209	6172	38
1962	4012	3606	405
1963	4014	4386	-372
1964	5985	6285	-301
1965	9723	9155	569
1966	4205	3730	475
1967	7226	7171	55
1968	6342	6494	-152
1969	7891	8228	-337
1970	3741	3559	182
1971	2223	2206	17
1972	6537	6891	-354
1973	5600	4457	1143
1974	4238	6152	-1914
1975	6285	NA	NA
1976	8997	NA	NA
1977	4779	NA	NA
1978	4809	NA	NA
1979	5260	NA	NA

[1] Historic gage records for WY 1947 were not available, so WAPCOS inflows were used.

Snow Water Equivalent Data

Reservoir operating rules for reservoirs that receive a significant portion of their inflow from snowmelt, as does Kajakai, usually take into account a forecast of runoff from snowmelt that will occur between the current date and the end of the snowmelt season. Should there be above normal or below normal water content in the snow pack at the end of the winter months, appropriate measures can be taken to help mitigate the reduced or excess volume of water in the system that coming year. Forecasts of inflow volumes from snowmelt require monitoring the volume of water contained in the snowpack, the snow water equivalent (SWE), upstream of the reservoir and estimating how much of that volume will eventually reach the reservoir.

Under Phase II of this study, historic snow water equivalent data were collected and analyzed, and a relationship between SWE and reservoir inflow was developed for inclusion into the regulation strategy for Kajakai Reservoir. See Appendix C for more information on SWE data collection in the Kajakai Reservoir watershed.

SWE information is currently gathered by using satellite imagery for all of Afghanistan. Using this information, spring runoff volume could be calculated using regression analysis or hydrologic modeling each year and the Kajakai Reservoir operations could be adjusted accordingly. However, a standard regression analysis could not be accomplished for Kajakai Reservoir because stream flow records (October 1947 through March 1980) and historic SWE data (1978 - present) do not overlap over a sufficient period of time. In the same respects, a hydrologic model could not be adequately calibrated given the limited amount of overlapping snowpack and stream flow data. Therefore, a statistical analysis was performed to compute and rank the historic volumes of the SWE data of record. A similar ranking was completed for the inflow volume into Kajakai reservoir for the period of record (1947-1979). Then, a regression analysis was performed on the frequencies records (inflow vs. SWE) to develop a relationship of SWE on February 1st vs. inflow to Kajakai. SWE and inflow volume percentiles are illustrated in Figure 3. The resulting SWE vs. inflow relationship was used to assist in the development of reservoir regulation rules that look at real time SWE data to set flood control pool target levels and project downstream deliveries as discussed in the reservoir regulation alternative analysis later in this report.

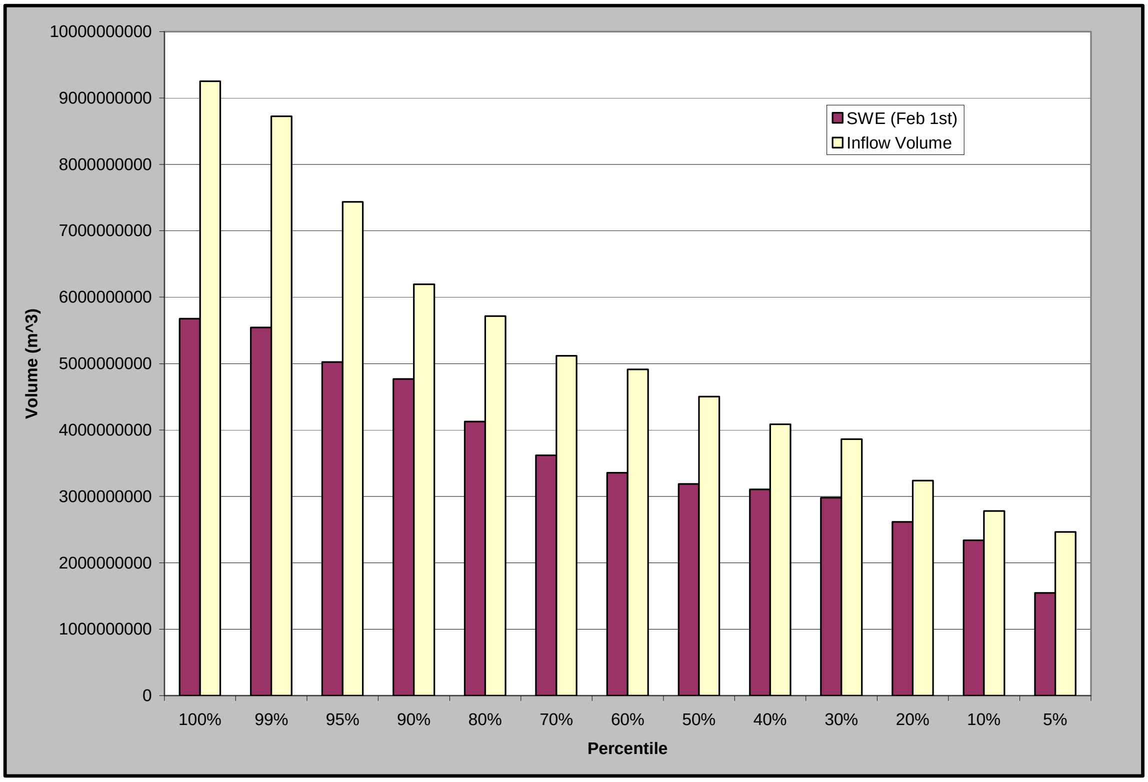

Figure 3. SWE vs Inflow Volume to Kajakai Reservoir percentiles

Water Supply Requirements

The main water supply requirements for flow in the Helmand River consist of irrigation demands in the Helmand Valley below Kajakai and flow requirements to Iran under an international agreement (per 1979 WAPCOS report). AED provided projected irrigation demands for 2008 based on recent agricultural studies of the Helmand Valley.

Experts familiar with the region stated that storage in Dahla dam is used for irrigation on the Arghandab River, downstream of the dam and that only under rare circumstances is there a measurable flow from the Arghandab River into the Helmand River. Therefore, for the purposes of this analysis, all irrigation demands in the Helmand and Nimroz Provinces are met by releases from Helmand Reservoir.

The monthly demands on Helmand releases used in this analysis include irrigation demands and Iran treaty flow requirements. They are listed in Table 2. Demands listed for the Lower Helmand Valley reflect the 2008 projected demand. Average monthly demands (cms) were converted to daily demands (cms) for input into the HEC-ResSim model by setting the daily average for each day of the month equal to the monthly average for that month.

A comparison of monthly inflow volumes versus the total demand is illustrated in Figure 4. This figure shows that the there is usually adequate water available in the system to meet the maximum demand requirements for a given year, but as is the case in most arid regions, the natural timing of the water supply does not meet the requirements of the agricultural community, so adequate storage must exist to hold the water until it is needed.

Table 2. Monthly demands (release requirements) from Kajakai Reservoir.

Month	Helmand (cms)	Nimroz (cms)	Iran Treaty (cms)	Total (cms)
Jan	68.1	89.0	34.7	191.8
Feb	0.0	95.9	78.2	174.1
Mar	83.7	110.7	73.1	267.5
Apr	99.4	115.8	31.1	246.3
May	103.2	116.0	9.0	228.2
Jun	97.5	100.6	19.7	217.8
Jul	89.6	85.1	13.7	188.4
Aug	93.0	68.2	9.4	170.6
Sep	89.2	60.5	2.3	152.0
Oct	71.8	69.9	5.0	146.7
Nov	72.2	79.1	12.7	164.0
Dec	89.7	86.1	23.0	198.8

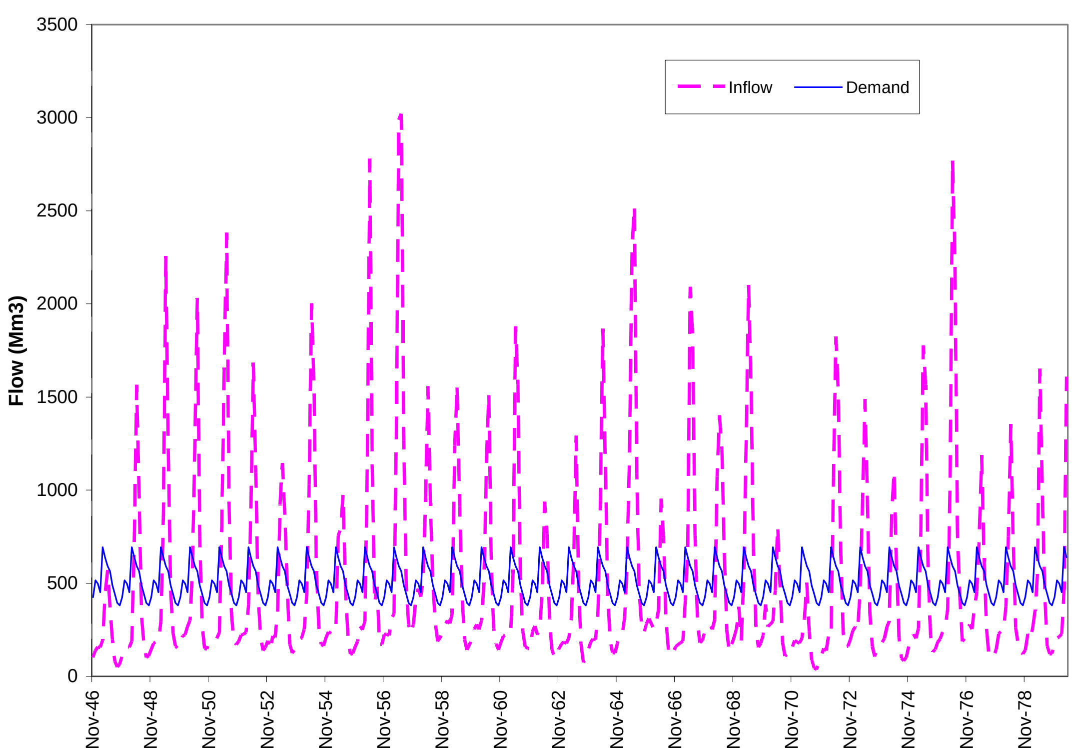

Figure 4. Historic monthly inflow vs. 2008 projected demand (monthly volumes).

HEC-ResSim Reservoir Model Operations

The original purpose of Kajakai Reservoir was for irrigation supply and flood protection. Later, power generating capabilities were added. Even so, the reservoir is primarily operated to meet irrigation requirements. For this analysis, HEC-ResSim was configured to operate to meet irrigation demands, and to the extent possible, release all flow through the power plant so that the maximum amount of power would be generated without sacrificing flows for irrigation and other downstream requirements.

Phase I – Physical Condition Analysis

For the Phase I analysis, where the objective was to quantify the benefit of installing the spillway gates and adding additional power generating capacity, three different "conditions" were modeled in HEC-ResSim. These conditions are described in Table 3.

Table 3. Helmand Dam Conditions Modeled in HEC-ResSim – Phase I

	Condition		
	Existing	**Proposed**	**Extended**
Spillway gates	No	Yes	Yes
Spillway crest elevation	1033.5 m	1036 m	1036 m
Top of conservation pool	1033.5	1045 m	1045 m
Top of gates	NA	1045 m	1045 m
Top of dam	1050 m	1050 m	1050 m
Power generation capacity	50 MW	50 MW	150 MW

For each condition (existing, proposed, and extended) within HEC-ResSim, Kajakai Reservoir was divided into three operational storage zones; (1) inactive, (2) conservation, and (3) flood control. The inactive zone is the zone that starts at the bottom of the reservoir pool and extends to the minimum operating level. For this study, the minimum operating level was set at elevation 995 m, and is based on historic operations that show this elevation is about the lowest level that the reservoir reached.

The conservation zone is the preferred zone for normal reservoir operations. The HEC-ResSim model was configured to make releases such that the level of the reservoir tries to stay within the conservation zone. While in the conservation zone, all releases are based on the objective of meeting downstream flow requirements (irrigation demands and Iran treaty requirements). The conservation zone extends from the top of the inactive zone to the bottom of the flood control zone. For the existing condition, the conservation zone extends from 995 m to 1033.5 m, which is the crest of the uncontrolled spillway. For the two conditions where the spillway gates installed, the conservation zone extends from 995 m to 1045 m, which is the design irrigation and power operating level specified in various project reports.

The flood control zone is the zone set aside for flood control storage. It extends from the top of conservation to the maximum operational elevation (assumed to be at elevation 1048 m for this analysis). So, for the existing condition, the flood control zone extends from 1033.5 m to 1048 m. For the proposed condition and extended, the flood control zone is much smaller, extending from 1045 m to 1048 m.

Simulations were run for all three conditions of Kajakai Reservoir for the 2008 projected demand as explained in the previous section on water supply requirements.

At the request of AED, an additional configuration of the HEC-ResSim model was created to study how raising the conservation level by 3 m (corresponding to a possible top-of-dam raise of 2 meters) would improve water supply and power generation. Previous design reports for the spillway on Kajakai Reservoir mention raising the top of dam elevation to 1052 m. Since raising the dam would allow for a larger conservation zone, the ability to meet irrigation and power generation requirements without reducing the amount of available flood control storage would be increased. To model this, the top-of-conservation elevation was changed from 1045 m to 1048 m and the elevation of the top-of-dam was changed from 1050 m to 1052 m. In effect, this “raised dam” analysis shows what could be gained by having the conservation level at 1048 m instead of 1045 m, whether the dam is raised or not, because only a very small portion of the flood control pool is used during the simulation.

Phase II – Reservoir Regulation Alternative Analysis

For the Phase II analysis, the objective was to quantify the benefits of different regulation alternatives assuming the spillway gates are installed. For this analysis, the “proposed” condition from Phase I was used as the reservoir configuration. Then, three different regulation alternatives were modeled in HEC-ResSim.

The first regulation alternative, termed “basic” for the purposes of this report, focuses on meeting full agricultural demand every year. The HEC-ResSim model was set up to release the full requirement without regard to reservoir level or ability to meet future demands. When the reservoir drops too low to meet the required demand, then the maximum release (inflow) is made. This is the simplest regulation alternative in that it does not require the reservoir operators to gather snow water equivalent data in the watershed upstream of Kajakai, nor does it require them to communicate water availability to downstream water users. The obvious drawback is that agricultural users will plan their crops based on full water supply, and if the release drop below the required demand, ground water pumping would have to ramp up to fill the need or corps would be lost.

The second regulation alternative, termed “snow water equivalent based (SWE based)”, takes into account the SWE in the Kajakai watershed on February 1st and then sets agricultural targets based that information for the upcoming year. This would allow farmers to plan appropriately for water deliveries, and only plant those crops that could be sustained based on a more accurate assessment of the water that will be available to them. This also will keep the natural flow signature of the Helmand River in tact, and have the least effect on the downstream ecosystem. The drawback of this operational alternative is that it requires the SWE data gathering effort and communication and coordination with downstream water users. The SWE operational logic is described in Table 4.

The third regulation alternative, termed “Flood Control” is similar to the SWE based alternative in that agricultural targets are determined based on measured snow water equivalent, but it also includes changing the conservation pool target level based on SWE to allow Kajakai to capture more flow during high runoff seasons, which would minimize peak flows downstream of Kajakai. This alternative has the benefits of the SWE based alternative, but it also allows for more development in the flood plain along the Helmand River downstream of Kajakai due to a more regulated flow regime. However, the more regulated flow regime will have a larger adverse impact on the downstream ecosystem. The pre-release drawdown logic is shown in Table 5. A draft reservoir regulation manual for Kajakai Reservoir that implements the “Flood Control” alternative is included in Appendix C.

Table 4. SWE-based regulation logic

If SWE on 01 Feb is		Release % of full demand
Greater than (billion m^3)	***and* less than or equal to (billion m^3)**	
4.3	*na*	100
3.5	4.3	75
1.8	3.5	50
na	1.8	25

Table 5. Flood control target storage logic

Snow Water Equivalent on 01 Feb (billion m^3)	Reservoir Target Elevation for 01 Mar (m)
<2.0	1036.0
2.0-3.0	1030.0
3.0-4.5	1025.0
>4.5	1020.0

Results – Phase I

Water Supply

The HEC-ResSim model for the Phase I analysis was configured to operate to meet 2008 projected water supply requirements in the lower Helmand Valley with no regard to status of snowpack in the upstream watershed. HEC-ResSim results for this demand are illustrated in Figure 5 for the existing and proposed conditions of Kajakai Dam using inflow from 1950 through 1960 (the entire period of record was run, these are shown for illustrative purposes). This snapshot of operation results illustrates the difference in reservoir pool elevations that would result from adding the gates. (Because the model was set up with water supply as a priority, results for the extended condition were very similar to the proposed condition so they were not added to the graph. The difference between the proposed and extended condition is obvious in the energy generation results shown later in this section.) The largest benefit from adding the gates is appreciated by looking at uncontrolled releases (reservoir level above top of conservation). Under existing condition, water passes through the uncontrolled spillway in almost every year, but when the gates are added, most of that water is retained for future use.

Annual water supply shortages based on historic inflows and 2008 projected demand for the existing and proposed conditions are illustrated in Figure 6 and Figure 7 respectively. It is clear from these graphs that the additional gates greatly decrease the water supply shortage in the Helmand Valley. Even with the gates installed, shortages occur 70% of the time years as shown in Figure 8, but the average annual shortage is reduced from 2139 Million m^3 to 634 Million m^3.

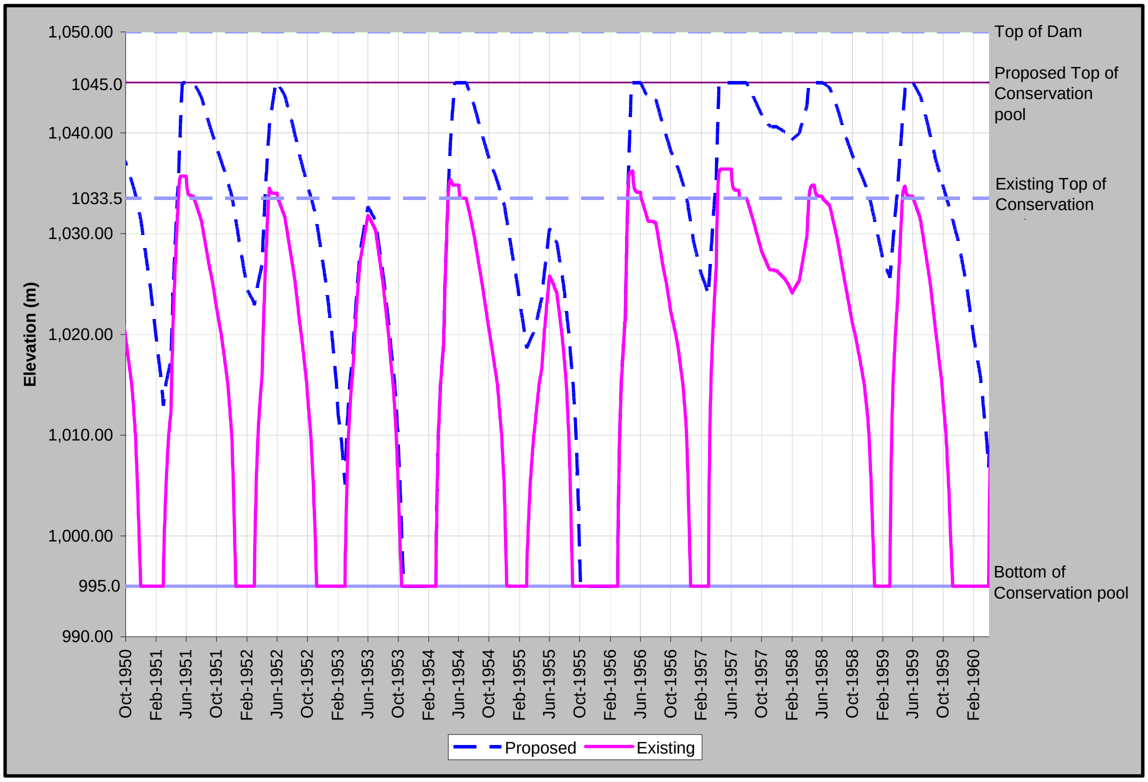

Figure 5. Reservoir pool elevation comparison for 100% demand, 1950 - 1960.

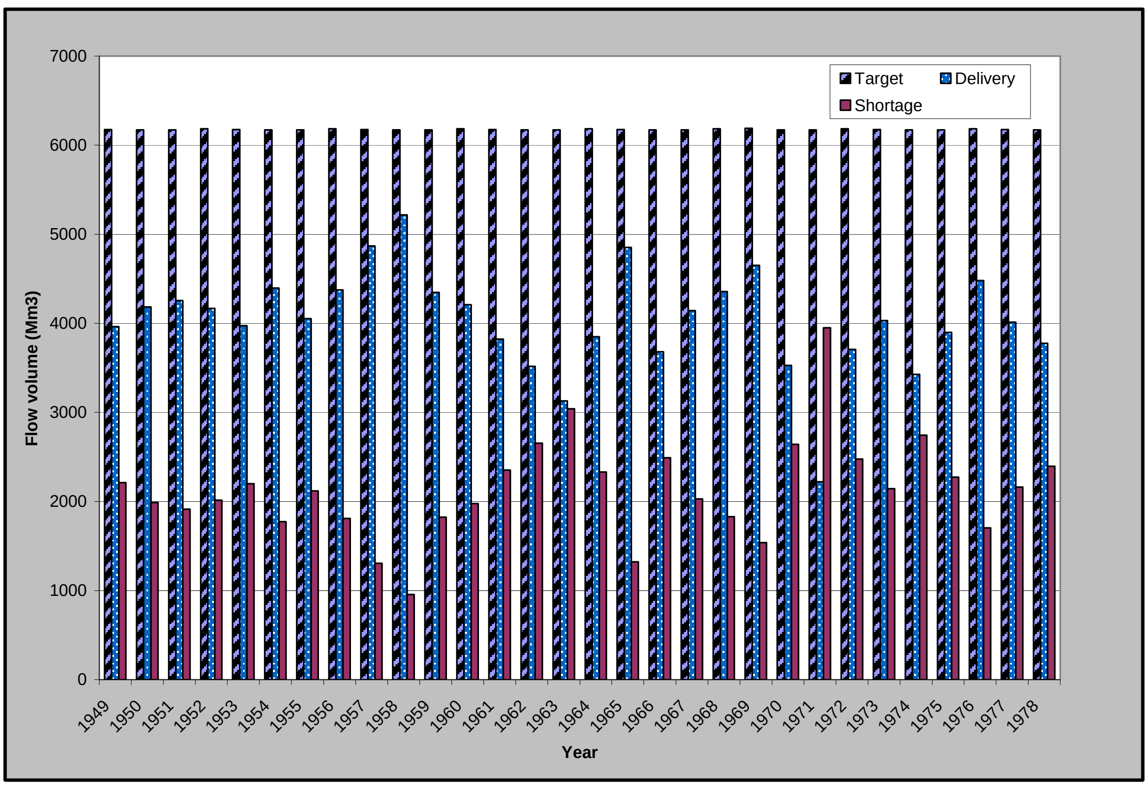

Figure 6. Annual deliveries and shortages – Without gates (existing condition)

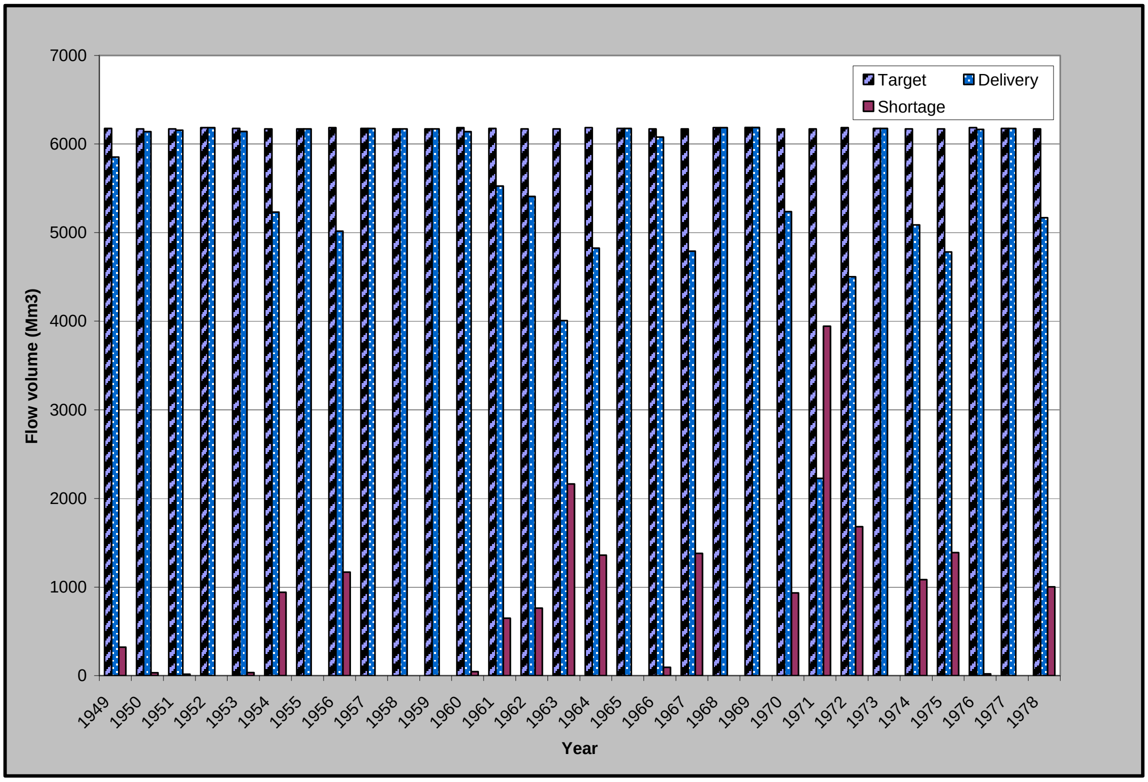

Figure 7. Annual deliveries and shortages – With gates (proposed condition)

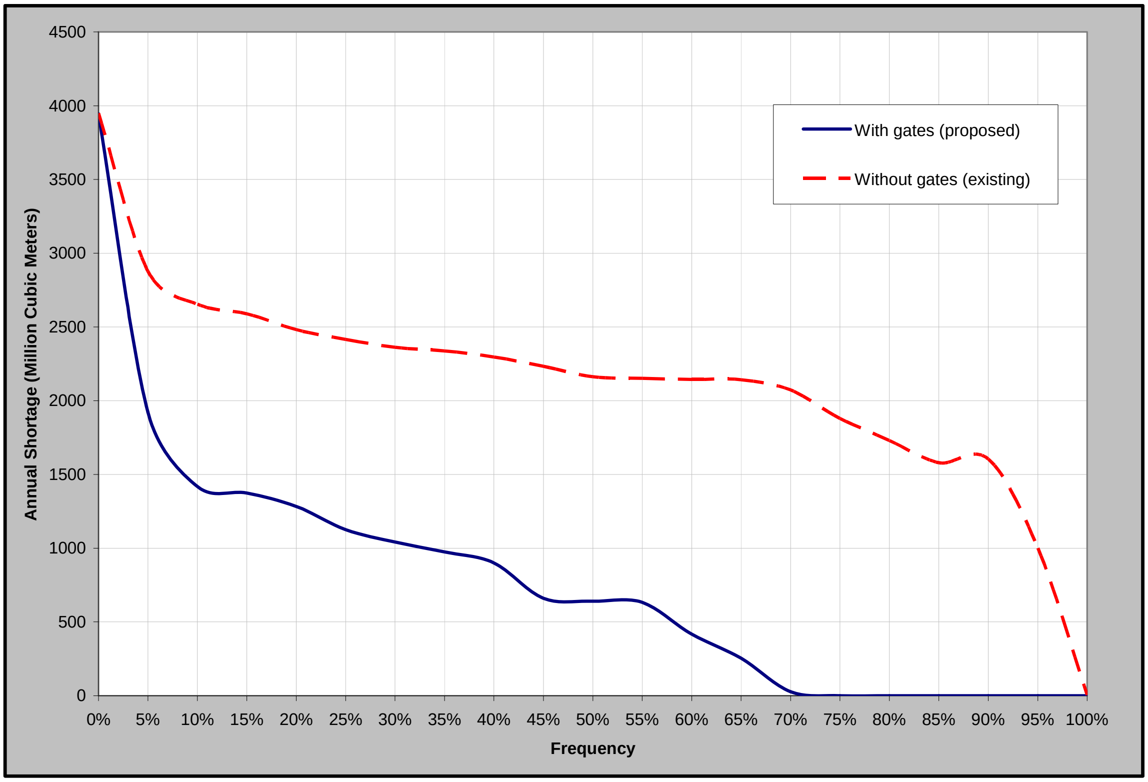

Figure 8. Phase I Kajakai condition comparison - Annual water supply shortage frequency

Power

Energy generation results based on historic inflows for the three conditions modeled in the Phase I analysis are shown in Figure 9. The energy frequency curve for the three conditions is show in Figure 10. The average annual energy generated for the existing condition (without gates) is 288 GWh. When the spillway gates are added (proposed condition), the average goes up to 389 GWh. Finally, when the power plant is extended from 50 MW to 150 MW capacity, the average annual energy generated is 745 GWh.

The small slope of the energy frequency curve for both of the conditions with only 50 MW installed capacity indicates that even when more water is available, the plant cannot take advantage of it to generate a proportionally increased amount of energy. With the additional capacity installed, during high flow years the energy generated does go up proportionally. Many factors should be considered before extending the power plant, but this analysis suggests that there is water available to take advantage of the additional generating capacity, especially after the spillway gates are installed.

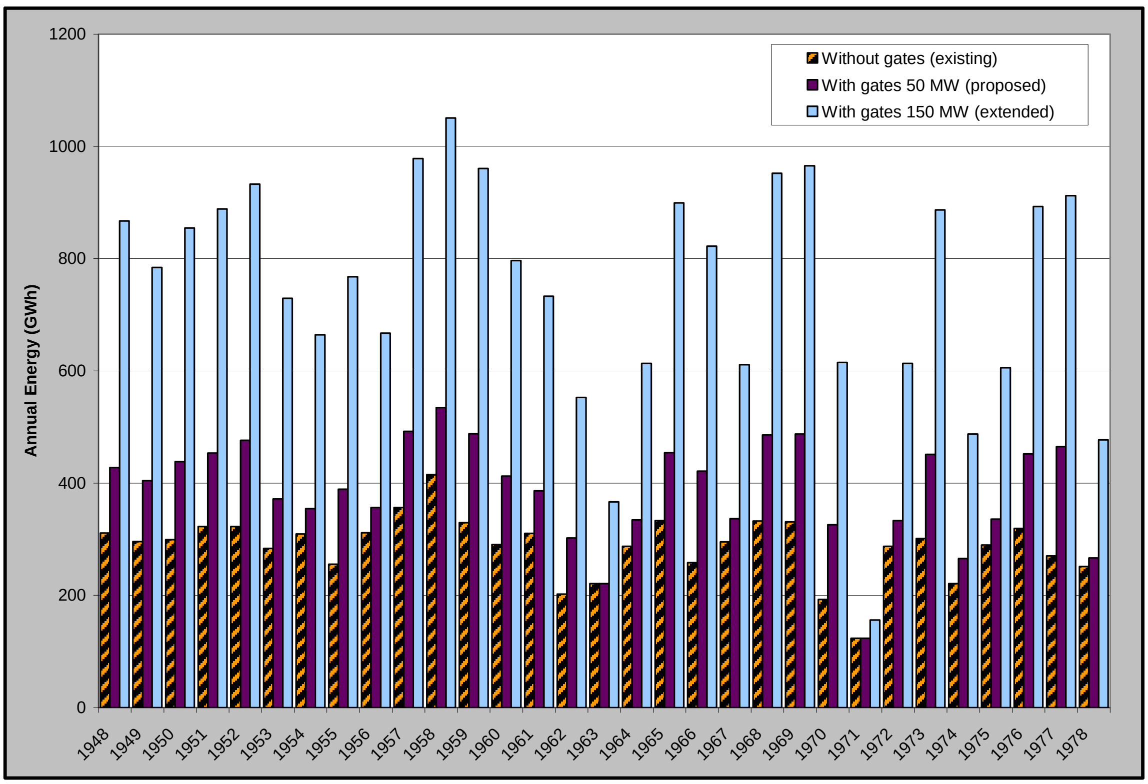

Figure 9. Phase I Kajakai condition comparison - Annual energy generation results

Figure 10. Phase I Kajakai condition comparison – Annual energy frequency curves

Raised Dam

Annual volumes of shortage for the proposed condition with the top-of-dam raised by 2 m are displayed in Figure 11. If the conservation level is raised by 3 m (corresponding to a possible top-of-dam raise of 2 m), the average annual shortage is reduced from 613 million m^3 to 521 million m^3. Given this modest decrease in shortages, unless the storage capacity of Kajakai Reservoir is greatly increased to allow for multiyear carryover storage of flows from very wet years, the ability to reliably meet 2008 projected demands with Kajakai Reservoir storage alone is limited. Additionally, other factors, such as displacing people living in the areas that would be inundated if the reservoir was raised must be considered. With the large population that lives in the proposed raised reservoir's pool, the relatively minor benefits associated with raising the reservoir would probably not outweigh the cost of relocating the population.

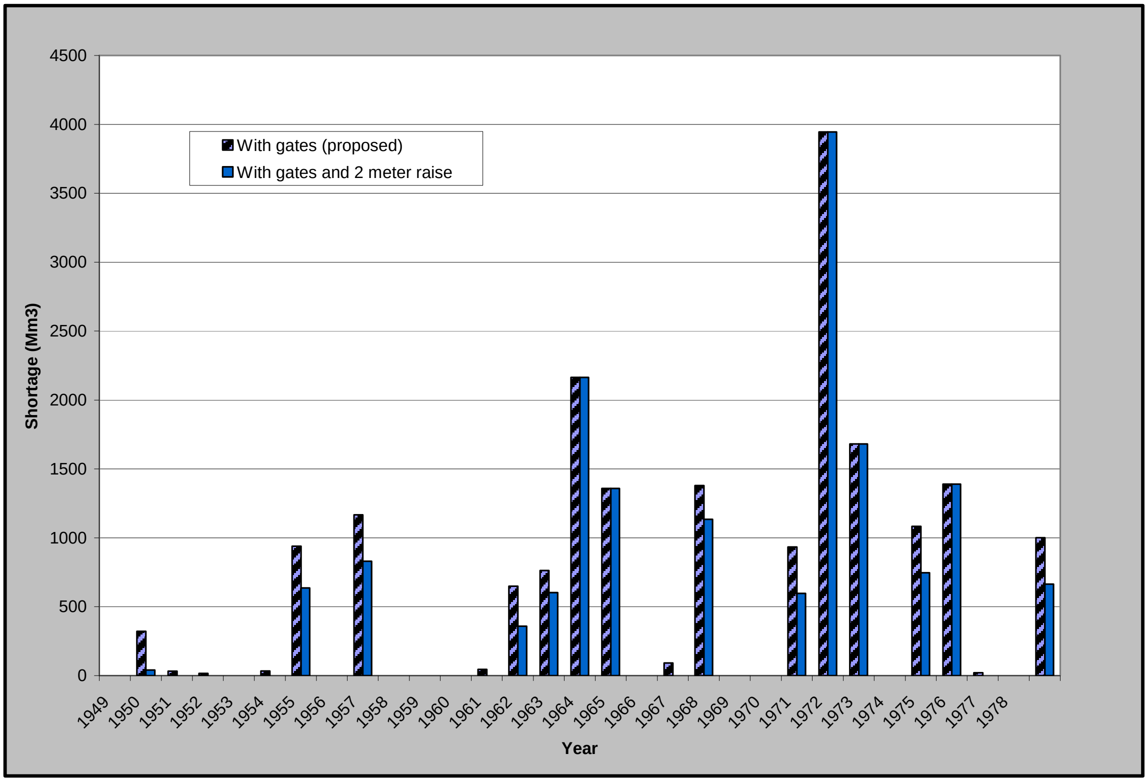

Figure 11. Annual Shortages – Proposed condition vs. raised dam

Results – Phase II

Regulation Alternative Analysis

The HEC-ResSim model for the Phase II analysis was configured with the gates installed on Kajakai Reservoir (proposed condition from Phase I). The goal of the Phase II analysis was to analyze alternative regulation strategies and provide results and a recommended regulation strategy. The three regulation strategies include:

(1) Basic regulation - Meeting full agricultural demand every year;

(2) SWE based regulation - Modifying agricultural targets based on measured snow water equivalent in the Kajakai watershed; and

(3) Flood control based regulation - Modifying agricultural targets based on measured snow water equivalent *and* making pre-releases to minimize peak flows downstream.

To compare regulation alternatives, three different aspects were analyzed: water supply efficiency, downstream flooding, and energy production.

Water supply was looked at from the standpoint of the water user's being able to rely on a pre-determined amount of water during the irrigation season. Under the basic regulation alternative, the projected water supply for downstream users always equaled the total demand. As would be expected, the basic regulation strategy led to significant shortages during drier years as illustrated in Figure 12. To assist downstream water users in planning their consumption (planting) for the upcoming year, it is a common practice for water supply reservoirs to forecast downstream water deliveries for the year based on knowledge of forecasted inflows. Forecasted inflows are usually based on the status of the snowpack in the reservoir's watershed. Therefore, the SWE based regulation and flood control based regulation alternatives both look at SWE on Feb 1st to set projected demands as described in Table 4. Water supply targets, deliveries, and shortages for these two alternatives are illustrated in Figure 13 and Figure 14. These figures show that basing projected deliveries on measured SWE can practically eliminate annual water supply shortages. And, even though the SWE based regulation alternatives (SWE based and flood control) reduce projected delivers during drier years, the average annual delivery over the period of record only drops from 5535 million m^3 to 5227 million m^3 for the SWE based alternative and 5230 million m^3 for the flood control alternative. The effect of this reduced overall delivery would be outweighed by allowing the farmers to plant the appropriate amount of crops for the upcoming season and not losing any due to water shortages.

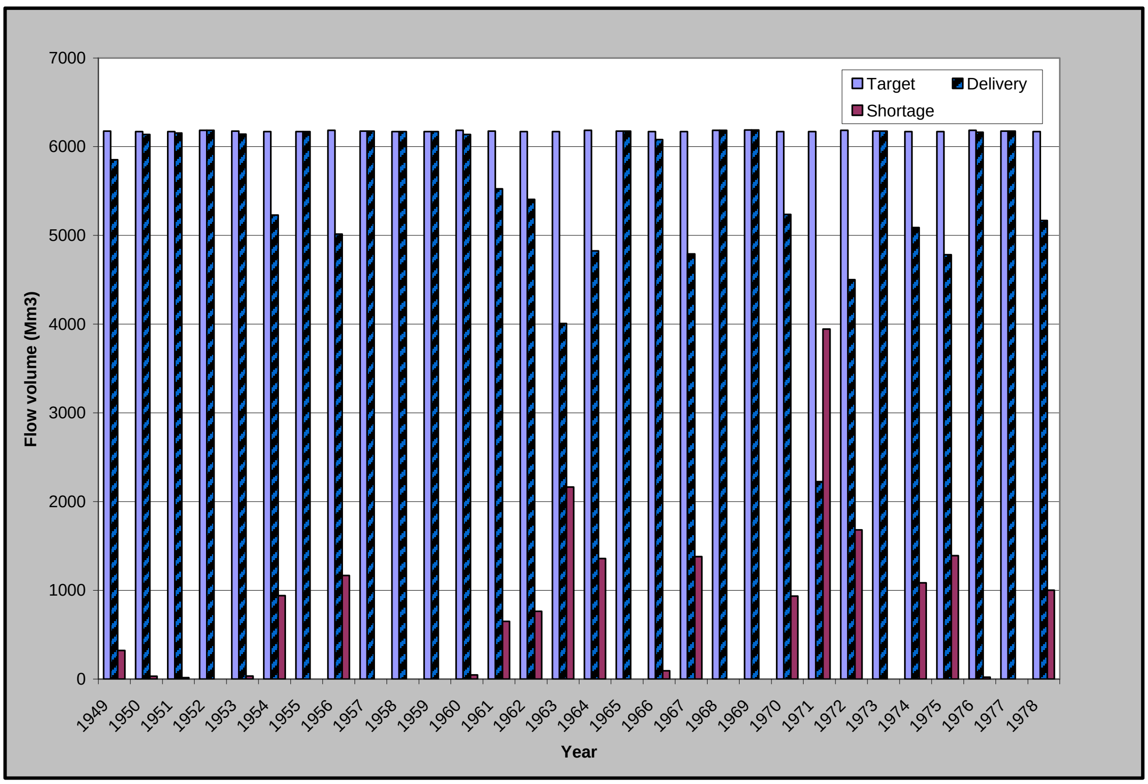

Figure 12. Annual deliveries and shortages – Basic regulation alternative.

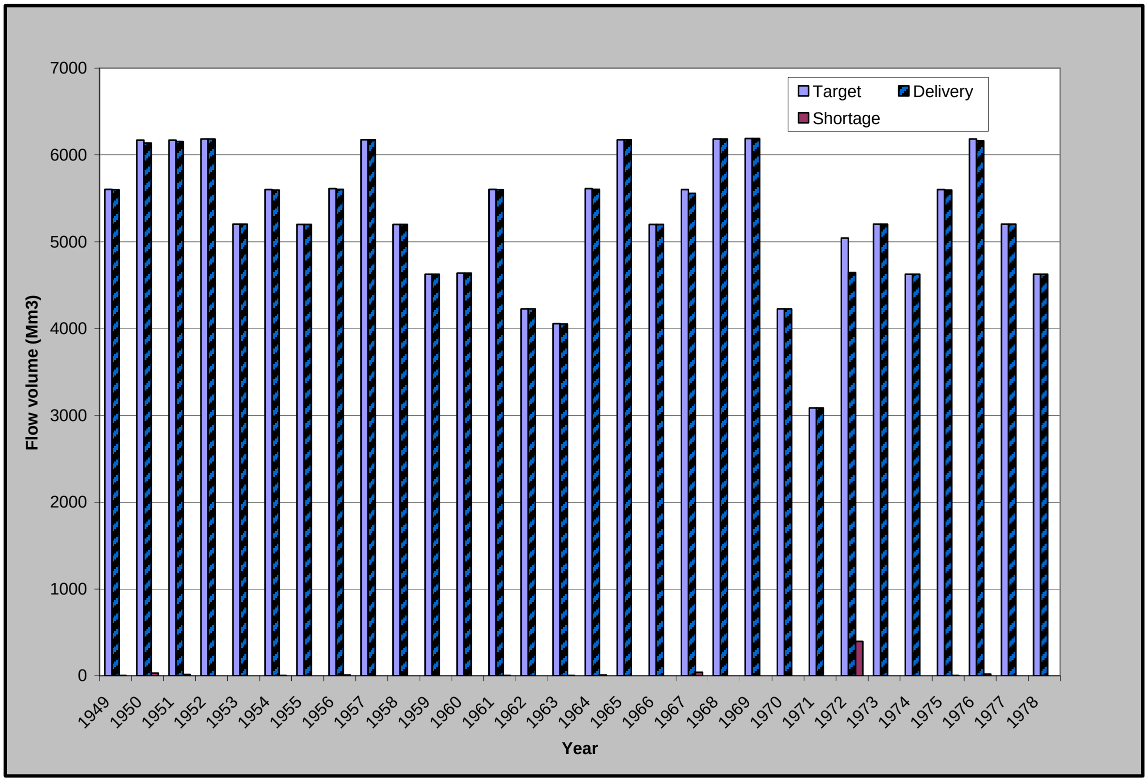

Figure 13. Annual deliveries and shortages – SWE based regulation alternative.

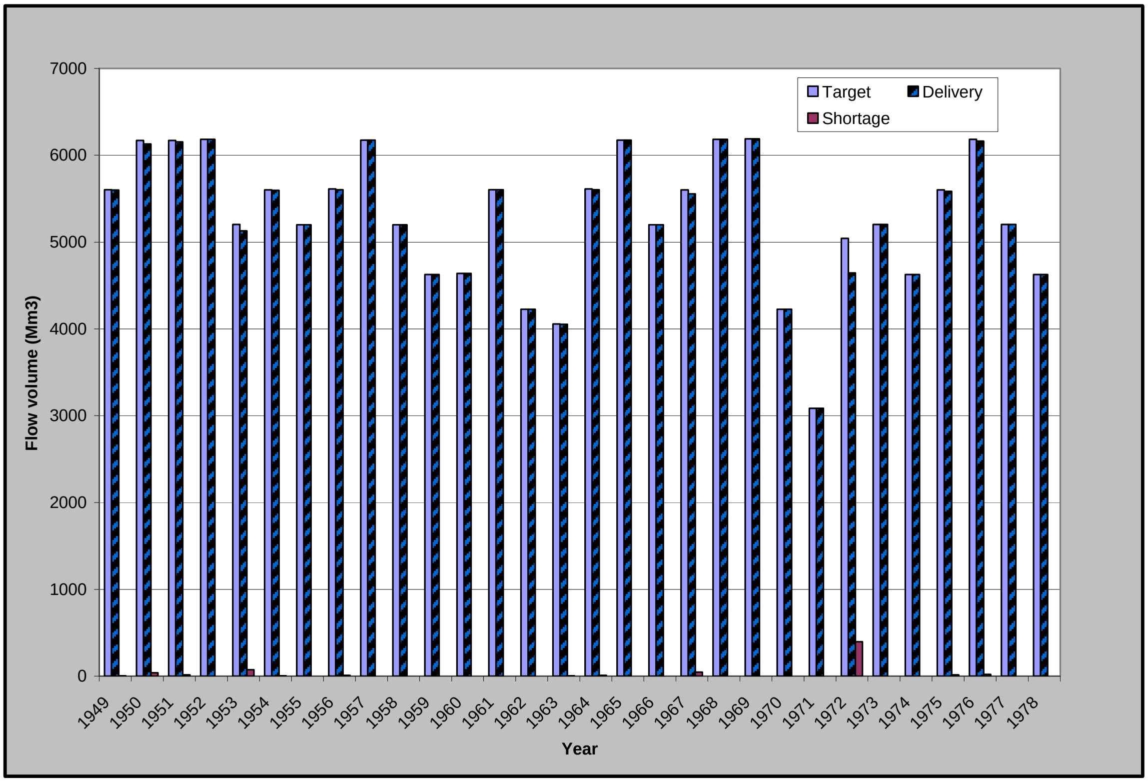

Figure 14. Annual deliveries and shortages – Flood control based regulation alternative.

Flood control effectiveness of the different alternatives was analyzed by computing the frequency of peak flows downstream of Kajakai for each alternative. The flood control regulation alternative was created to minimize peak flows downstream of Kajakai while still projecting water deliveries based on measured SWE. The flood control regulation alternative looks at measured SWE upstream of Kajakai to set target storage levels each spring. If measured SWE is high, then the target storage level in Kajakai is lower, so that more room is available to store the expected inflow. The relationship between target storage level and SWE is shown in Table 5. Peak flow frequency relationships are plotted in Figure 15 for each regulation alternative. The effectiveness of the flood control alternative is noticeable in that it reduces the peak of the low frequency, high flow events when compared to the other 2 alternatives. Interestingly, the basic regulation alternative reduced the peak flows downstream of Kajakai more than the other alternatives for the events ranging in frequency from 10% to 65%. The reason is that by reducing demands during drier years, Kajakai reservoir does not empty out as frequently when operated using SWE based deliveries. This leads to the peak flows being higher under the flood control regulation than the basic regulation alternative. However, flood control regulations are targeted at reducing the most damaging, highest flow peaks and not on reducing the peak of the more common, non-damaging events. The benefit of making pre-releases based on SWE is noticeable as the flood control regulation alternative significantly reduces downstream peak flows when compared to the SWE based alternative for most of the rarer events. Also, while it seems the basic regulation could be useful for flood control regulation, the drawback is that the minimum flows are much lower due to Kajakai reservoir being empty more often as shown in Figure 16. This could have devastating effects on the ecosystem downstream of Kajakai.

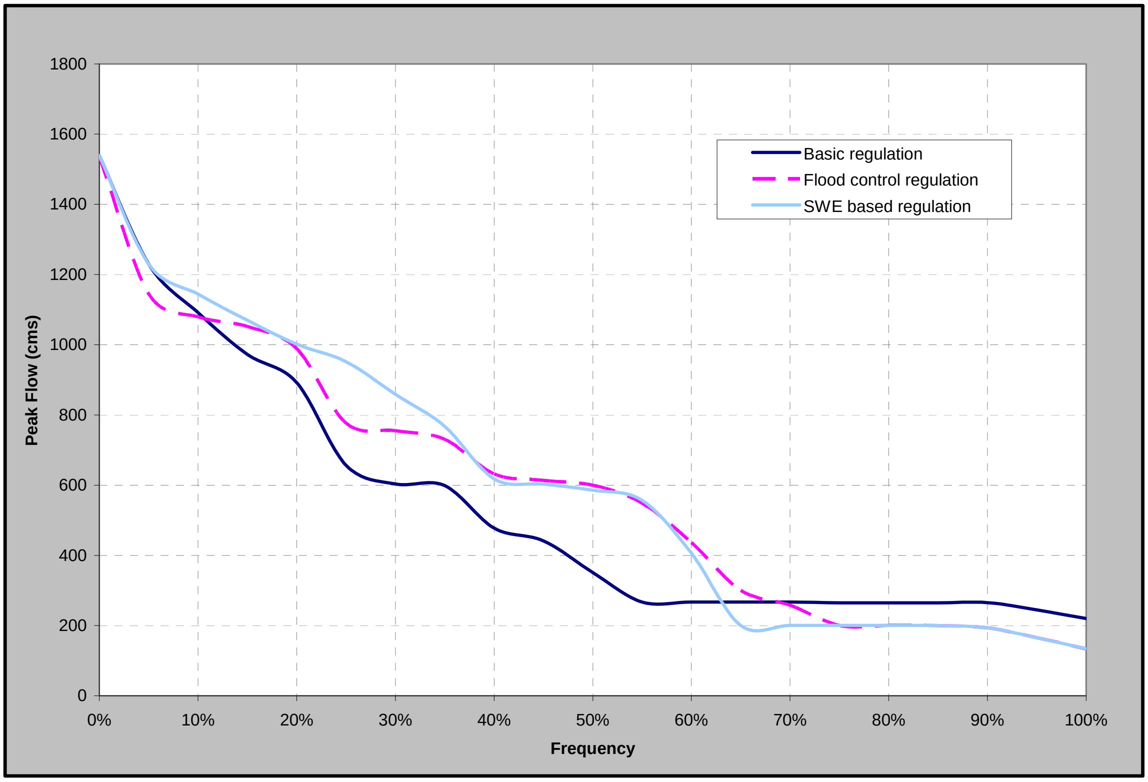

Figure 15. Regulation alternative analysis - Peak flow frequency

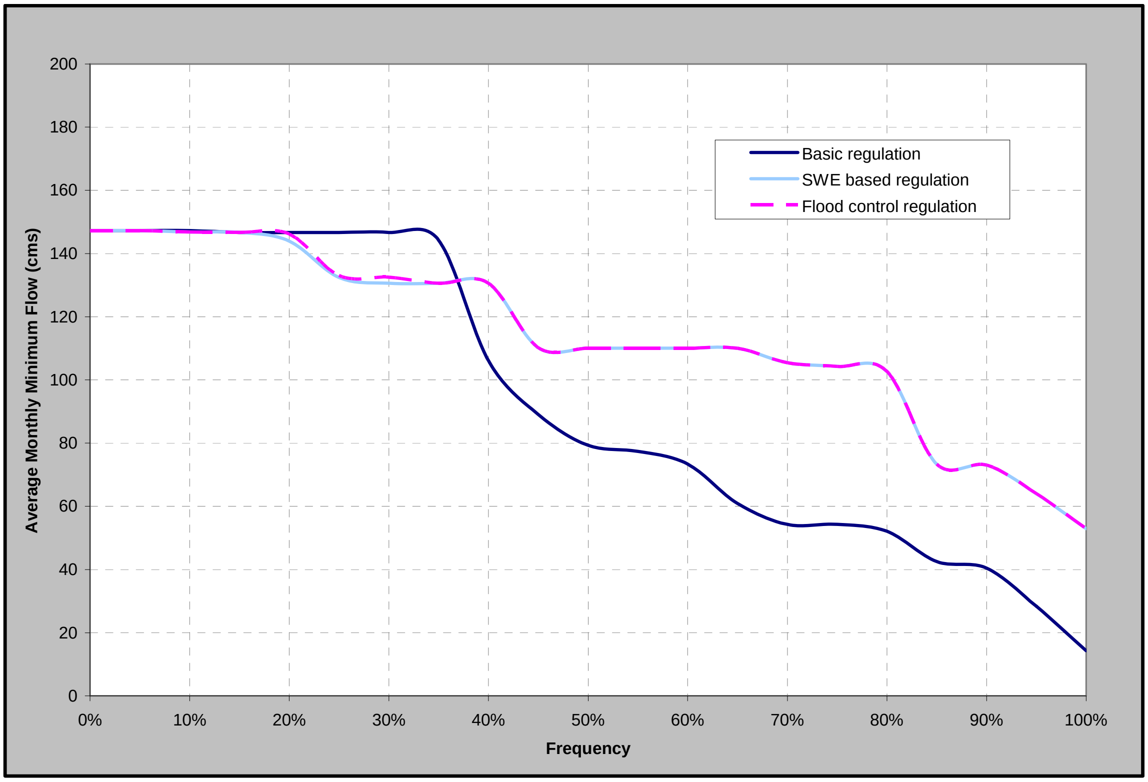

Figure 16. Regulation alternative analysis - Average monthly minimum flows

The final metric used to compare regulation alternatives was energy production. Energy generation results computed for the period of record using the three regulation alternatives modeled in the Phase II analysis are shown in Figure 17. The energy frequency curve for the three conditions is show in Figure 18. All regulation alternatives are based on 50 MW installed capacity at the Kajakai power plant. The average annual energy generated for the basic regulation alternative is 389 GWh. For the flood control alternative, the average goes up to 486 GWh, and for the SWE based alternative, the average is 505 GWh.

Looking at the energy frequency curves, it is important to point out that the regulation alternatives that reduce deliveries based on SWE in the upstream watershed not only produce more energy, but they produce a much more consistent amount of energy on an annual basis. This occurs because Kajakai Reservoir is rarely emptied to meet downstream demands, and the higher head in the reservoir contributes to greater power generation capabilities.

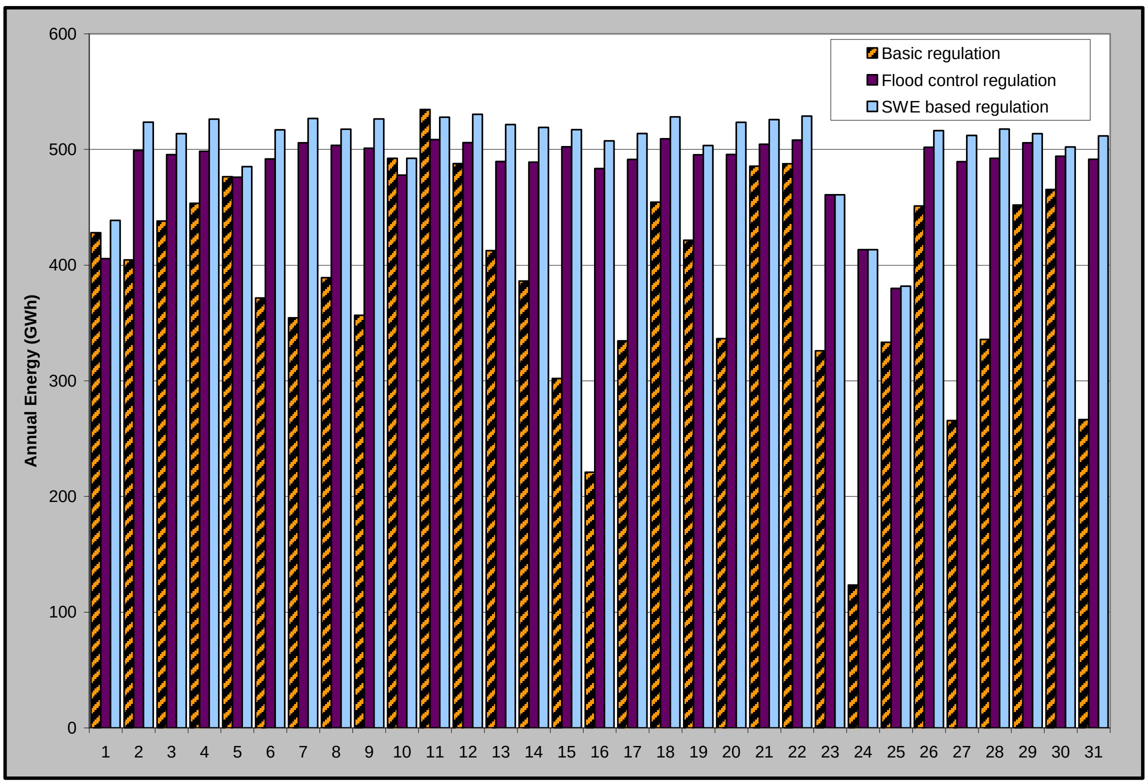

Figure 17. Regulation alternative analysis – Annual energy production results

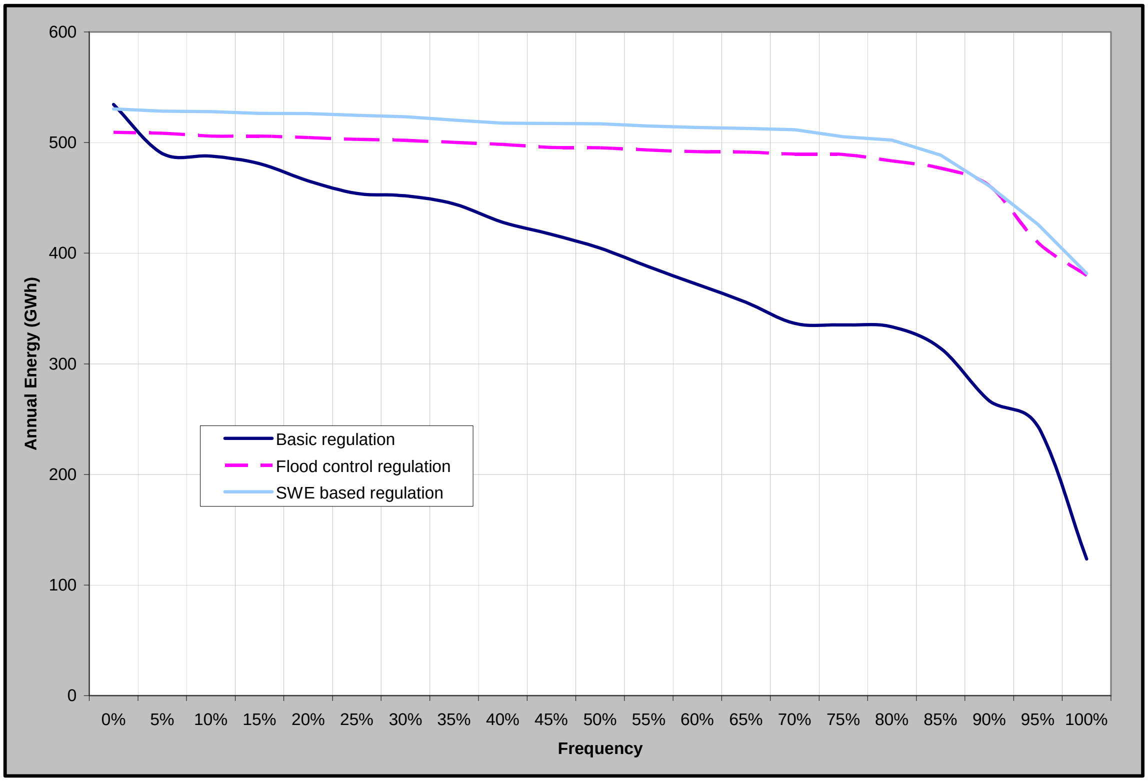

Figure 18. Regulation alternative analysis – Annual energy frequency curves

Probable Maximum Flood (PMF) Analysis

The proposed condition (with gates) from the Phase I analysis was used as the basis to analysis the capability of Kajakai Reservoir to pass the PMF. To perform the analysis, two additional conditions were created:

1. Existing system + proposed gates + emergency spillway (fuse plug elevation 1047.7)

2. Existing system + proposed gates + raised dam to elevation 1052 + emergency spillway (fuse plug elevation 1049.7).

A major assumption for the first condition created in the PMF analysis (1) was that since the reservoir elevation was not going to be raised to 1052, that the fuse plug elevation would also be 2m lower (1047.7).

A PMF analysis had previously been performed by HARZA in 1976. It was reviewed as part of this analysis and determined to be as accurate as could be expected given the limited amount of data available.

The HARZA PMF was simulated in HEC-ResSim using the two new conditions described above. For Condition 1 (top-of-dam 1050), the model results showed that if the elevation of the reservoir is at or near the top-of-flood pool when the PMF hits, the dam will be overtopped. If the reservoir starts empty in Condition 1, it can pass the PMF, but that is not a reasonable starting storage for a PMF analysis. Condition 2 was run to verify that the original spillway design (based on top-of-dam 1052) would pass the PMF under wet conditions (reservoir starting at or near top-of-flood). Model results show that for Condition 2 the reservoir is not overtopped, even when the reservoir is full when the PMF hits.

To get an estimate of the modifications that would be required on the emergency spillway to allow it to pass the PMF, the width of the emergency spillway was increased in Condition 1 until it was able to pass the PMF flow. Preliminary findings suggest that the emergency spillway would have to be widened by approximately 20 meters (from 95 m to 115m) before it could safely pass the PMF.

Conclusions

Results from the Phase I analysis suggest that even with the additional gates installed, Kajakai Reservoir will have limited ability to keep up with agricultural demands in the Lower Helmand Valley. However, large water supply and power generation benefits are gained from the proposed modifications (additional gates and power turbines) to Kajakai dam.

Total average annual inflow into Kajakai Reservoir is 5939 million m^3, which is slightly less than the 2008 projected demand in the lower Helmand River valley. Results from this analysis indicate water supply shortages will occur in 100% of the years under the existing condition (no gates) and 70% of the years if the gates are installed, but those shortages will be much less severe (reduced by approximately 75% on average).

Results from the Phase II analysis are summarized in Table 6. These results suggest that developing a reservoir regulation plan that bases water supply deliveries for the year on snowpack conditions in the Kajakai watershed will not only be economically beneficial to downstream water users, it will generate more energy and reduce flooding downstream of Kajakai for the largest flood events. A trade-off analysis between flood damage reduction (minimizing peak flows) and ecosystem health should be completed before a final regulation alternative is determined. Given that limited development has occurred to date in the floodplain downstream of

Kajakai reservoir, it is important to weigh the environmental costs or and regulation modifications now, before flood damage based economics becomes a larger component of the decision.

Table 6. Phase II summary of results

Regulation Alternative	Water Supply		Flood Control	Energy Production
	Mean annual delivery (Mm^3)	Mean annual shortage (Mm^3)	5% chance event peak flow (cms)	Mean annual energy (GWh)
Basic	5535	613	1230	389
SWE based	5227	18	1230	505
Flood control	5230	21	1144	486

It is recognized that meeting irrigation demands is the primary goal of Kajakai Reservoir. However, in order to develop the most efficient and economically justified operating rules for Kajakai Reservoir, a trade-off analysis between power generation, water supply, and flood damage reduction should be performed. To do so, economical factors related to power generation, flood damage, and agriculture must be derived for the Helmand Valley and other areas that may benefit from power generation and releases at Kajakai. Data necessary to support a trade-off analysis were not available at the time of this study.

While other results could be presented, this report attempts to provide enough information so that USAID and others can make decisions for the immediate future as well as for long term regulation decisions if and when the spillway gates are installed. It should also be recognized that flexibility should be exercised in drawing absolute conclusions from the Phase I study results.

References

Louis Berger Group Inc. "Kajakai Hydroelectric Project Condition Assessment, Dam Safety Assessment Report", April 2004.

U.S. Army Corps of Engineers. "HEC-ResSim, Reservoir System Simulation User's Manual" *Report CPD-82*, Hydrologic Engineering Center, U.S. Army Corps of Engineers, September 2003.

Water and Power Development Consultancy Services Limited. "Feasibility Report for the Extension of Kajakai Hydro Electric Power Station", January 1979.

Appendix A – Kajakai Reservoir Physical Data

This appendix contains the physical description of the *existing* condition (original construction) of the reservoir as well as the *proposed* and *extended* conditions of the reservoir.

Table 7 shows the elevation - storage - area relationship for Kajakai Reservoir, which does not change between the three conditions. This elevation – storage – area relationship was obtained from AED and represents the condition of the reservoir as of 2006 based on recent sedimentation studies.

Table 8 shows the composite outlet capacity of the irrigation outlet works, which consists of three valves and does not change between the three conditions. The storage – outlet capacity relationship for the irrigation valves was estimated based on values found in the WAPCOS report. Data for this relationship were reviewed by AED.

Table 9 shows the outlet capacity of the original uncontrolled spillway as well as the proposed gated spillway. The crest elevation of the spillway is raised to 1034 under the proposed condition, which leads to a slightly lower total release capacity. The storage – outflow relationship for the existing spillway was provided by AED. The design storage – outflow relationship for the proposed gated spillway could not be found in any existing reports, so one was estimated to show the effects of raising the spillway crest. For the proposed and extended conditions, the spillway capacity is the same as the existing; only the elevation for each point on the curve is 0.5 m higher.

Table 10 shows the storage – outflow relationship for the power plant under existing and proposed conditions. The storage – outlet capacity relationship for the existing and extended power plants were provided by AED.

Table 7. Kajakai reservoir storage relationship.

Elevation (m)	Storage (1000 m3)	Area (ha)
970	0	1000
975	6291000	1643
980	39821000	2287
985	80946000	2930
990	129966000	3574
995	184819000	4217
1000	234962000	4860
1005	282243000	5504
1010	346710000	6147
1015	452073000	6791
1020	629572000	7434
1025	860626000	8077
1030	1162709000	8721
1035	1505036000	9364
1040	1947340000	10008
1045	2454042000	10651
1046	2563369000	10780
1047	2675675000	10908
1048	2790680000	11037
1049	2910130000	11166
1050	3034197000	11294

Table 8. Kajakai reservoir composite irrigation outlet capacity – irrigation valves.

Elevation (m)	Maximum Release (cms)
970.0	0
980.0	99.09
990.0	127.41
1000.0	155.72
1010.0	181.20
1020.0	201.02
1030.0	218.01
1033.5	223.67
1040.0	233.58
1045.0	240.66

Table 9. Kajakai reservoir outlet capacity – spillway.

Elevation (m)	Existing uncontrolled spillway release (cms)	Proposed gated spillway max release (cms)
1033.5 (1034*)	**0**	**0**
1035	**340**	**0**
1036.0	**708**	**0**
1039.75	**1048**	**1000**
1041.93	**1557**	**2000**
1043.76	**2123**	**3000**
1045.38	**2831**	**4000**
1046.86	**3539**	**5000**
1048.24	**4304**	**6000**
1049.55	**5238**	**7000**
1050.0	**6229**	**7500**

* With gates installed, spillway crest is raised by 0.5 m.

Table 10. Kajakai reservoir outlet capacity – power plant.

Elevation (m)	Existing turbines (cms)	Extended turbines (cms)
1008.0	**71.0**	**144.9**
1018.0	**78.5**	**160.2**
1028.0	**85.3**	**174.2**
1038.0	**91.7**	**187.1**
1040.0	**92.9**	**189.6**
1045.0	**89.5**	**195.7**
1048.0	**86.9**	**199.2**

Appendix B - Snowpack Data for the Kajakai Reservoir and Helmand River Watersheds

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Introduction

The Helmand River is the longest river in Afghanistan. The Helmand rises in the Hindu Kush, some 50 km west of Kabul, flows roughly southwest for about 1130 km, and empties into the Seistan swamps, the Hamun Lake Hamun-i-Helmand, at the Iran-Afghan border (Fig. 1). The Helmand River is an important component of the water resources of Afghanistan. The flow in the Helmand River is produced by rainfall and snowmelt. Snowmelt provides a significant, although currently unknown, portion of the runoff, especially in the late winter and spring. The Kajakai Reservoir (Fig. 1), located on the Helmand River, is a significant hydraulic structure that has the potential to improve the water management capabilities of the Helmand River. The area of the Kajakai Reservoir watershed is approximately 46,850 square kilometers and comprises about 26% of the 181,422 square kilometers of the Helmand River watershed. The elevation range of the Kajakai Reservoir watershed extends from about 500 to 5000 m (Table 1, Fig. 2). The elevation of the Helmand River watershed ranges from about 0 to 5000 m (Table 1).

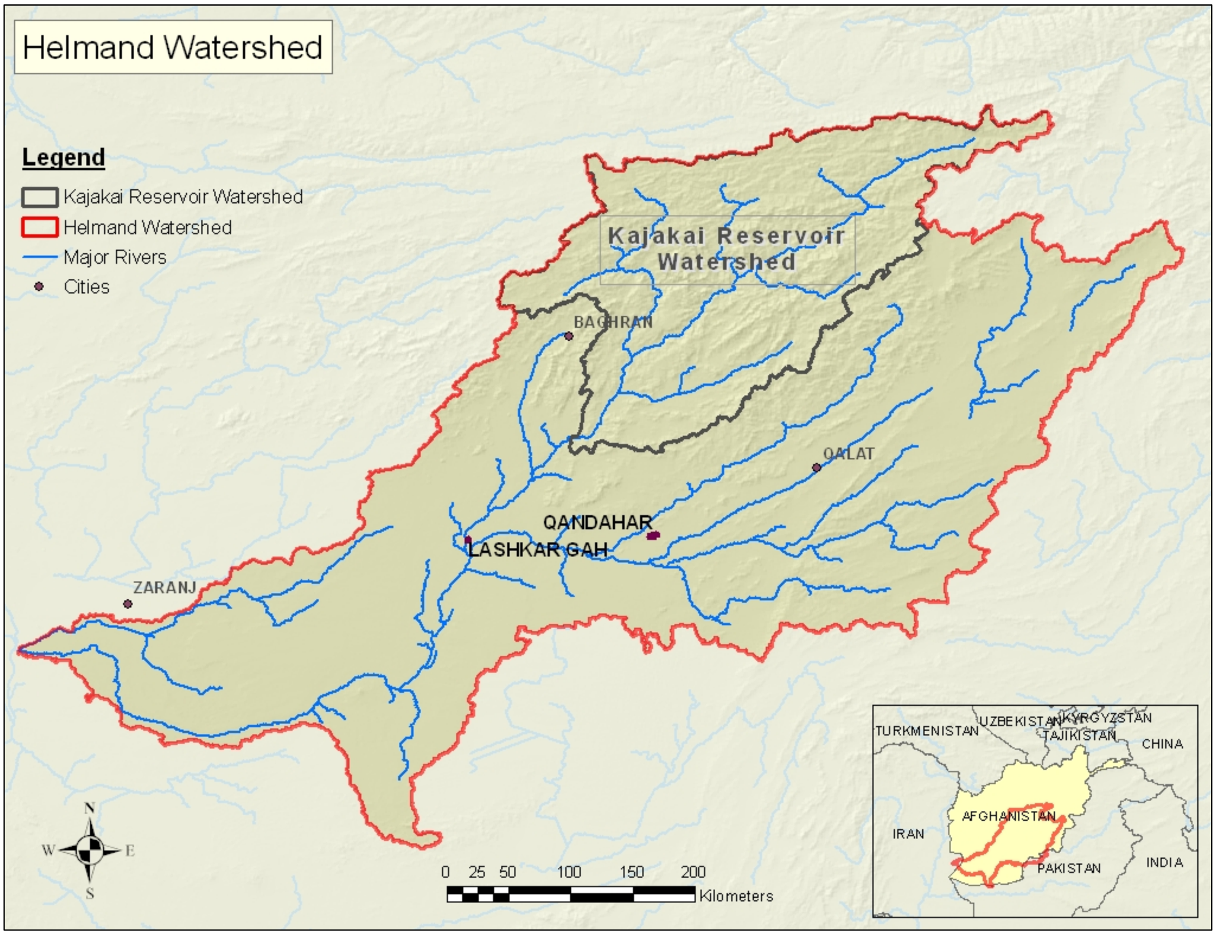

Figure 1. Helmand watershed.

Table 1. Areas of the Kajakai Reservoir watershed and the Helmand River watershed by elevation band.

Elevation band (m)		Area (km^2)	
Lower Range	**Upper Range**	**Kajakai Reservoir Watershed**	**Helmand River Watershed**
0	500	0	2,006
500	1,000	37	42,319
1,000	1,500	3,500	30,830
1,500	2,000	7,172	25,015
2,000	2,500	8,769	40,924
2,500	3,000	14,690	21,748
3,000	3,500	10,175	14,975
3,500	4,000	2,224	3,217
4,000	4,500	264	339
4,500	5,000	19	49

This report describes the historical snowpack conditions in the overall Helmand River watershed and the sub-watershed upstream of Kajakai Reservoir. This historical snow data will be used in the development of a reservoir operation model of the Kajakai Reservoir. Satellite imagery was the source of the historic snow data. Two satellites were used: the Special Sensor Microwave/Imager (SSM/I), one of several sensors carried on Defense Meteorological Satellite Program (DMSP) satellites, and the Scanning Multi-channel Microwave Radiometer (SMMR). SSM/I data are available weekly over the Helmand Reservoir from the winter 1987-88 through the present; and the SMMR data are available monthly for the period 1978-1987. The following sections of this report provide background information on remote snow measurements by satellites; describe the processing of the data, and display results in the form of time series and annual statistics.

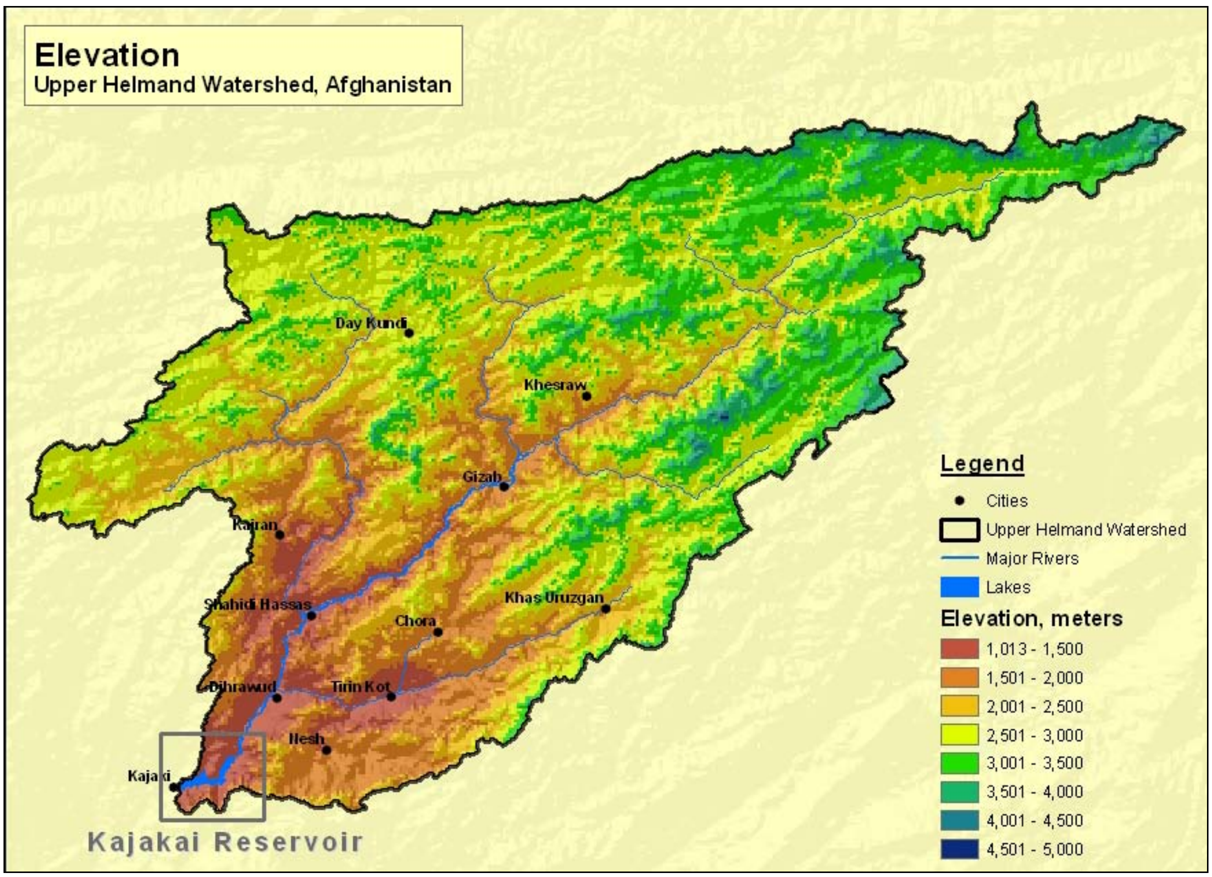

Figure 2. Elevations in the Kajakai Reservoir.

Remote Snow Measurements by satellite

Satellite imagery can provide information on the snow-covered area (SCA), snow water equivalent (SWE), and snow depth. In this study we concentrated on SWE, the snow parameter of most interest for water resource management. Satellite measurements from which SWE can be derived are available from two satellites: the Scanning Multichannel Microwave Radiometer (SMMR) and selected Special Sensor Microwave/Imagers (SSM/I) (Armstrong et al. 2005, Knowles et al. 2002). The satellite data are processed and available in 25-km equal-area grids, so each grid cell covers an area of 625 sq. km. The satellite measurements represent the mean SWE for each grid cell. Measurements made during the coldest time of day as these sensors are less reliable over wet snow, and are used to estimate the snow properties. The measurements are processed to account for the presence of vegetation, remove false measurements, account for variations in the satellite swath coverage, and remove noise in the SWE signal caused by temporary atmospheric phenomena (e.g. warm, precipitating weather fronts).

The SWE measurements can be affected by a number of factors that can apply to the Helmand watershed (Armstrong et al. 2005). Mountainous areas with large topographic variability can return low SWE values. Samples from these areas contain a mixed signal from a large footprint that may include deep snow on north-facing slopes, snow-free south-facing slopes, wind-scoured alpine areas, etc. Areas containing melting snow or wet snowpacks typical of maritime snow conditions return low or no SWE values, because the microwave emission from liquid water overwhelms scattering from the snowpack. Shallow or intermittent snow during fall and early winter typically does not result in sufficient microwave scattering to reliably detect SWE values. It is not clear how much the SWE estimates for the Helmand River watershed have been impacted by these factors. Armstrong et al. (2005) also caution against comparisons between the SMMR and SSM/I data sets. They suggest that there are enough differences between SMMR and the SSM/I sensors to raise doubts as to the validity of time-series analysis of SWE across the sensor break (July to August 1987). They recommend "that users view the SWE data sets derived from SMMR (1978 to July 1987) and from SSM/I (August 1987 to present) as separate time series, with a potential discontinuity in the summer of 1987."

GIS Analysis

SMM/I Data. The SSM/I data were provided by NSIDC in the Equal-Area Scalable Earth Grid (EASE-Grid). The data in each grid cell corresponded to the SWE in each cell in millimeters. The EASE-GRID projection parameters are listed in Table 2. Each data file consisted of an array of binary, 16-bit signed, little-endian integers (the least significant byte of the data field was stored at the lowest memory address). The majority of the data, acquired from 3 August 1987 to 21 March 2005, was provided as a weekly product that had undergone quality control at NSIDC. Each weekly product spanned seven days, from a Monday to a Sunday. Each cell in the weekly product represented, after the quality control procedures described above had been accomplished, the maximum SWE that had been detected in that cell over the seven-day period. A second group of data, acquired from 28 March 2005 to 27 March 2006, was provided as a daily product that had not undergone quality control by NSIDC.

The SSM/I files were imported to Arc Grid format using the Workstation ArcInfo *imagegrid* command. A header file, listed in Table 3, was created for each SSM/I file prior to the conversion to be used by the *imagegrid* command. The *projectdefine* command was run to assign the EASE Grid projection parameters (Table 1) to the imported grid.

Table 2. EASE Grid projection parameters.

Projection	lambert_azimuthal
Units	meters
Radius of the sphere of reference	6371228
Longitude of center of projection	0° 0′ 0″
Latitude of center of projection	90° 0′ 0″
False easting (m)	0
False northing (m)	0

Table 3. ArcInfo header file information.

nrows	721
ncols	721
nbands	1
nbits	16
byteorder	I
layout	bsq
ulxmap	–9024309
ulymap	9024309
xdim	25067.525
ydim	25067.525

The Grid *con* function was used to remove values in the imported grids that were greater than or equal to 65000. These data represent negative numbers in the original SSM/I SWE data and are incorrectly converted due to limitation in the ArcInfo *imagegrid* function. These values were not needed for analysis and were removed from the grid.

The daily SSM/I files (acquired from 28 March 2005 to 27 March 2006) were processed into a weekly product using the Grid *max* function on each group of seven daily grids that spanned from a Monday to a Sunday. The *max* function determined the maximum value on a cell-by-cell basis for each group of seven input grids. This was consistent with the process that NSIDC used to create the weekly product covering the time frame of 3 August 1987 to 21 March 2005. Occasionally, seven days of data were not available for the weekly product, in which case the five or six days available were used.

Once the SSM/I data had been converted to ArcInfo grids and were all in a consistent weekly format, the data were processed to determine the total SWE volume of the Kajakai Reservoir watershed as well as the entire Helmand watershed. First, the weekly SSM/I grids were converted to a map projection suitable for watershed analysis in Afghanistan using the *project* command. The projection parameters used are listed in Table 4a. GIS information describing the watershed boundaries is also listed in Table 4b.

Table 4a. GIS projection parameters.

Projection	albers equal area
Units	meters
Parameters	
First standard parallel	31° 0′ 0.000″
Second standard parallel	37° 0′ 0.000″
Central meridian	67° 0′ 0.000″
Latitude of origin	23° 0′ 0.000″
False easting (m)	0.00000
False northing (m)	0.00000

Table 4b. GIS information.

Helmand Watershed boundary source data reference: Title: HYDRO1K basins dataset for Asia Developer: USGS EROS Data Center Publication date: unknown. Data are derived from USGS GTOPO30 DEM, which was completed in 1996. Watersheds were derived from nominal 1-km elevation data. The readme file associated with the data is at: http://edc.usgs.gov/products/elevation/gtopo30/hydro/readme.html#DataDistribution
Kajakai Reservoir Watershed source data reference: Title: Watershed_171103 Developer: Afghanistan Information Management Services (AIMS) Publication date: December 2003 Resolution of data is unknown. Metadata file is attached. Metadata indicates boundaries were delineated from 500 and 100 m DEM along with field verification. http://www.aims.org.af/home/sroots.asp?seckeyz=z2&secido=2&seckeyt=a10

The grids were re-sampled to a 1-km resolution using the Grid *resampl*e function. This was done to allow accurate “clipping” of the SSM/I SWE data to the watersheds. A grid of the Kajakai Reservoir Watershed for use in the SWE analysis was generated using a watershed boundary shapefile obtained from the Afghanistan Information Management Service data (Table 4b). The polygon shape with the watershed name attribute of “Upper Helmand” was extracted from the shapefile and converted to a grid with a resolution of 1 km using the ArcInfo Grid function *polygrid*. The watershed boundary for the Helmand watershed was derived from the HYDRO1k dataset (Table 4b). The HYDRO1k as_dem elevation grid was used in ArcInfo to delineate the Helmand watershed within Afghanistan. The hydrologically correct as_dem grid was processed using the ArcInfo Grid functions *flowdirection* and *watershed*. Results from the function *flowaccumulation* were used to define the watershed pour point. The results from the watershed function were compared with the HYDRO1k as_bas watershed coverage to determine the boundary of the Helmand basin in Afghanistan and create the 1 km grid for use in the SWE analysis. The total snow water volume contained in each watershed was calculated using the Grid *zonalstats* command on the 1-km SSM/I SWE grids with the *sum* option and a grid of each watershed (also at a 1-km resolution) as the zone grid. This sum of snow water height was then multiplied by the area of a grid cell (1×10^6 sq. m) and then converted to cubic meters.

SMMR Data. Identical steps were used to process the SMMR as the SMM/I data. The MMR data were provided by NSIDC in the Equal-Area Scalable Earth Grid (EASE-Grid). The data in each grid cell corresponded to the SWE in each cell in millimeters. The EASE-GRID projection parameters are listed in Table 2. The data covered the time period from November 1978 through July 1987. A significant difference between the SMMR and the SMM/I weekly product is that the SMM/I weekly product represented the *maximum* SWE that was measured in each cell over the week, while the SMMR monthly product represented the *average* SWE that was measured in each cell over the month. The SMMR data were converted to Arc Grid format as described above. Once the SSM/I data had been converted to ArcInfo grids, the data were processed to determine the total SWE volume of the watershed upstream of the Kajakai Reservoir as well as the entire Helmand watershed.

SWE Results

SMM/I Data. The SMM/I data resulted in a time series of SWE volumes for the Kajakai Reservoir watershed and the entire Helmand watershed after the processing described above. Each SWE value represented the maximum SWE detected in the seven-day period that began on the date associated with the SWE data value. The time series began on 03 August 1987 and continued to the present. There were two gaps of missing data: 07 December 1987 through 04 January 1988 (5 weeks) and 27/ June 2005 through 12 September 2005 (12 weeks). There was very likely no or very little snow on the ground during the second data gap. The weekly SSM/I SWE results are shown in Figure 3. It can be seen that there exists considerable year-to-year variation in the maximum SWE. The maximum SWE detected each year is listed in Table 5. There is a slight downward trend in the maximum SWE detected each year for the entire Helmand watershed but little or no trend in the Kajakai Reservoir watershed. It is interesting to note that a record maximum SWE for the entire Helmand watershed was detected during the winter of 2004-05 and a record minimum during the winter of 2005-06. A record minimum was also recorded for the minimum SWE for the Kajakai Reservoir watershed in 2005-06.

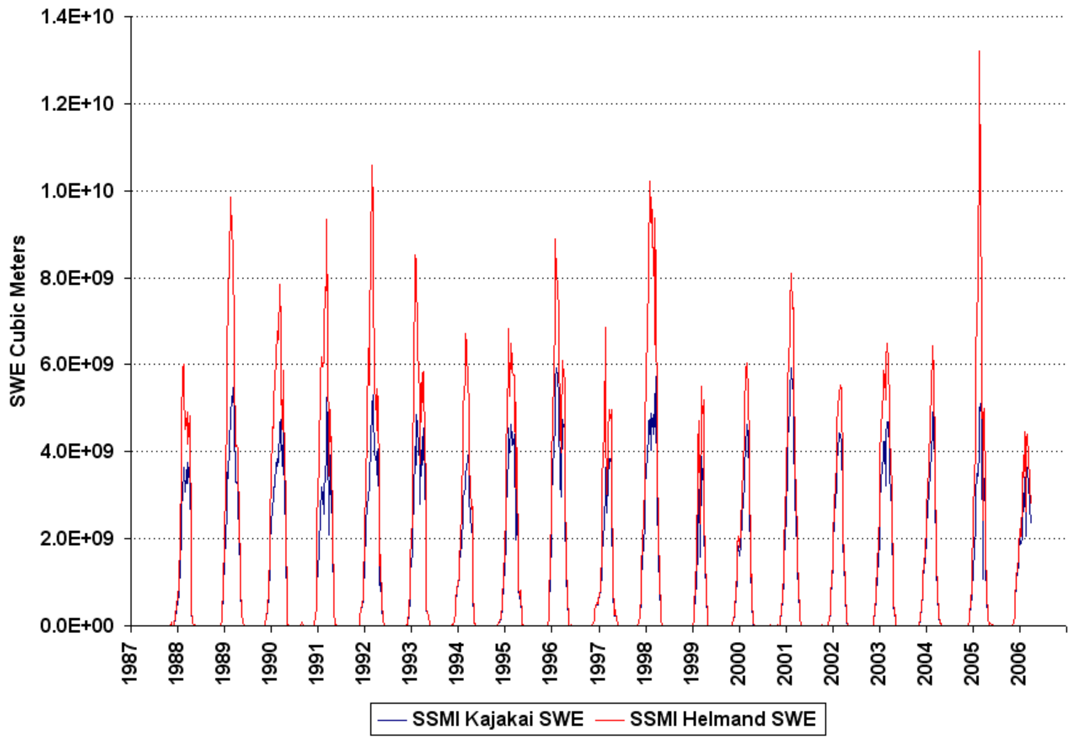

Figure 3. Time series of SMM/I data.

Table 5. Maximum SWE detected each year based on SMM/I data. The date given is the start of the seven-day period in which the maximum occurred.

Kajakai Reservoir		Helmand watershed	
Date	SWE ($m^3 \times 10^9$)	Date	SWE ($m^3 \times 10^9$)
4-Apr-1988	3.785	15-Feb-1988	6.023
6-Mar-1989	5.463	20-Feb-1989	9.855
12-Mar-1990	4.739	19-Feb-1990	6.778
11-Mar-1991	5.263	11-Mar-1991	9.342
2-Mar-1992	5.307	24-Feb-1992	10.583
8-Feb-1993	4.851	25-Jan-1993	8.521
21-Mar-1994	3.987	28-Feb-1994	6.721
13-Feb-1995	4.632	30-Jan-1995	6.844
5-Feb-1996	5.933	29-Jan-1996	8.900
7-Apr-1997	3.914	17-Feb-1997	6.869
23-Mar-1998	5.743	2-Feb-1998	10.229
8-Mar-1999	3.894	8-Mar-1999	5.498
6-Mar-2000	4.620	28-Feb-2000	6.030
12-Feb-2001	5.938	12-Feb-2001	8.091
18-Feb-2002	4.422	4-Mar-2002	5.530
3-Mar-2003	4.695	3-Mar-2003	6.482
23-Feb-2004	4.909	23-Feb-2004	6.437
28-Feb-2005	5.095	21-Feb-2005	13.220
20-Feb-2006	3.695	6-Feb-2006	4.449

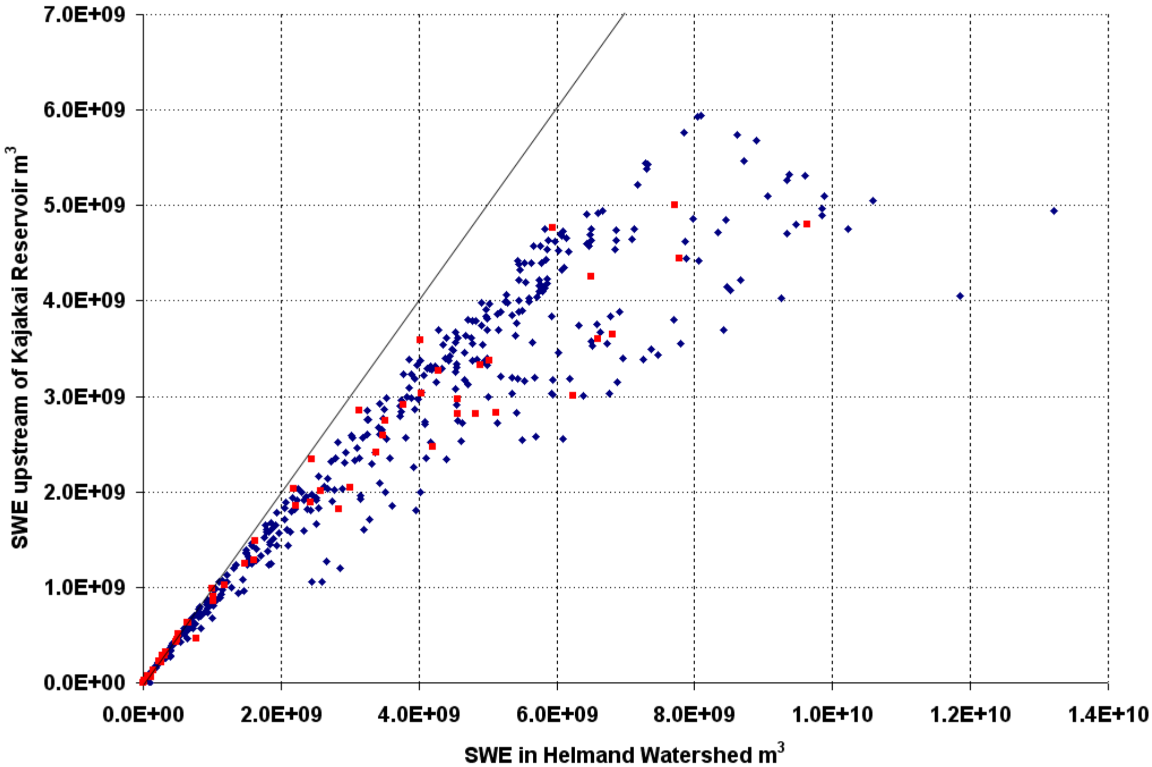

Figure 4. Comparison of the SWE volume upstream of the Kajakai Reservoir and the entire Helmand watershed Each blue data point represents the maximum SWE recorded during the same seven-day period (SMM/I data), and each red data point represents the average SWE recorded during the same month (SMMR data).

A comparison between the SWE volume detected over the Kajakai Reservoir watershed and the entire Helmand watershed is shown in Figure 4. Each data point shown represents the maximum SWE recorded during the same seven-day period for the Helmand watershed and the Kajakai Reservoir sub-watershed. It can be seen that when the SWE values are relatively low, less than about 1×10^9 m^3, almost the entire snowpack of the Helmand watershed is located in the Kajakai Reservoir watershed, and as a result, the values are nearly identical. At larger SWE volumes, the snow-covered area spreads beyond the Kajakai Reservoir watershed, and the total for the Helmand watershed becomes larger than that of the Kajakai Reservoir.

The annual statistics of the SWE volumes were determined by analyzing the weekly SSM/I data. The analysis was done using DSSVUE (U.S. Army Corps of Engineers 2006) in the following manner. First, the time series of weekly SSM/I values was entered into DSSVUE, taking care to assign missing values to weeks that occurred during the two data gaps. The weekly data could not be analyzed directly because there are not an integer number of seven-day periods in one year. This resulted in the day of the year on which the data were collected varying from year to year, with a period of between 6 to 11 years before any given day was repeated. The weekly time series was converted to a daily time series to overcome this problem. All the days of each seven-day period were set equal to the value of SSM/I SWE volume recorded at the start of the period. No interpolation was attempted because there was no information available on when the maximum SWE was recorded during each seven-day period, only that the maximum SWE had occurred sometime during the period. The daily SWE values were then analyzed using the *cyclic analysis* math function of DSSVUE. This determined the average, a range of percentiles, the standard deviation, the maximum, and the minimum for each day of the year. Values were selected for the 1st and 15th of each month, starting on 15 November and going through 1 June. The values for the Kajakai Reservoir watershed are listed in Table 6 and displayed in Figures 5–7. The values for the entire Helmand watershed are listed in Table 7 and displayed in Figures 8–10.

Table 6. SWE Percentiles based on SMM/I data of the Kajakai Reservoir watershed. The SWE volumes are given in $m^3 \times 10^9$.

		Percent of years with SWE volumes less than							
Date	**Min**	**5**	**10**	**25**	**50**	**75**	**90**	**95**	**Max**
15-Nov	0.000	0.000	0.000	0.000	0.010	0.028	0.049	0.071	0.079
1-Dec	0.000	0.000	0.000	0.001	0.135	0.305	0.442	0.444	0.581
15-Dec	0.000	0.000	0.088	0.415	0.538	1.040	1.134	1.199	1.574
1-Jan	0.000	0.000	0.597	1.197	1.432	1.919	2.025	2.031	3.174
15-Jan	0.101	0.101	0.742	1.714	2.517	2.740	3.552	3.612	3.884
1-Feb	0.673	0.673	1.610	2.673	3.187	3.852	4.721	4.949	5.675
15-Feb	1.848	1.848	2.054	3.026	3.983	4.225	4.851	5.763	5.938
1-Mar	3.129	3.129	3.555	3.636	4.328	4.909	5.095	5.098	5.437
15-Mar	1.060	1.060	2.793	3.320	3.894	4.679	4.862	5.263	5.321
1-Apr	0.733	0.733	0.979	2.092	3.293	3.792	4.003	4.164	4.734
15-Apr	0.051	0.051	0.572	0.842	1.672	3.219	3.617	4.059	4.572
1-May	0.017	0.017	0.037	0.110	0.271	0.627	0.854	0.944	1.908
15-May	0.000	0.000	0.000	0.007	0.044	0.126	0.281	0.314	0.823
1-Jun	0.000	0.000	0.000	0.000	0.000	0.021	0.029	0.056	0.084

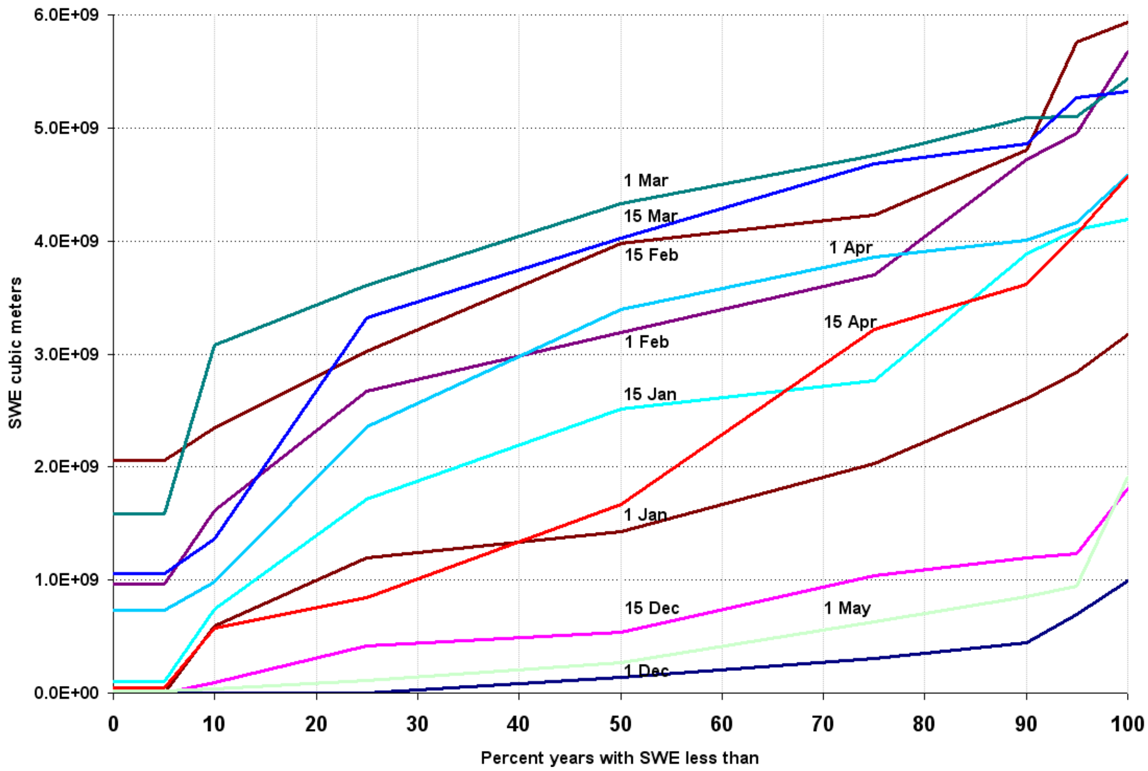

Figure 5. SWE percentiles for the Kajakai Reservoir watershed for given dates.

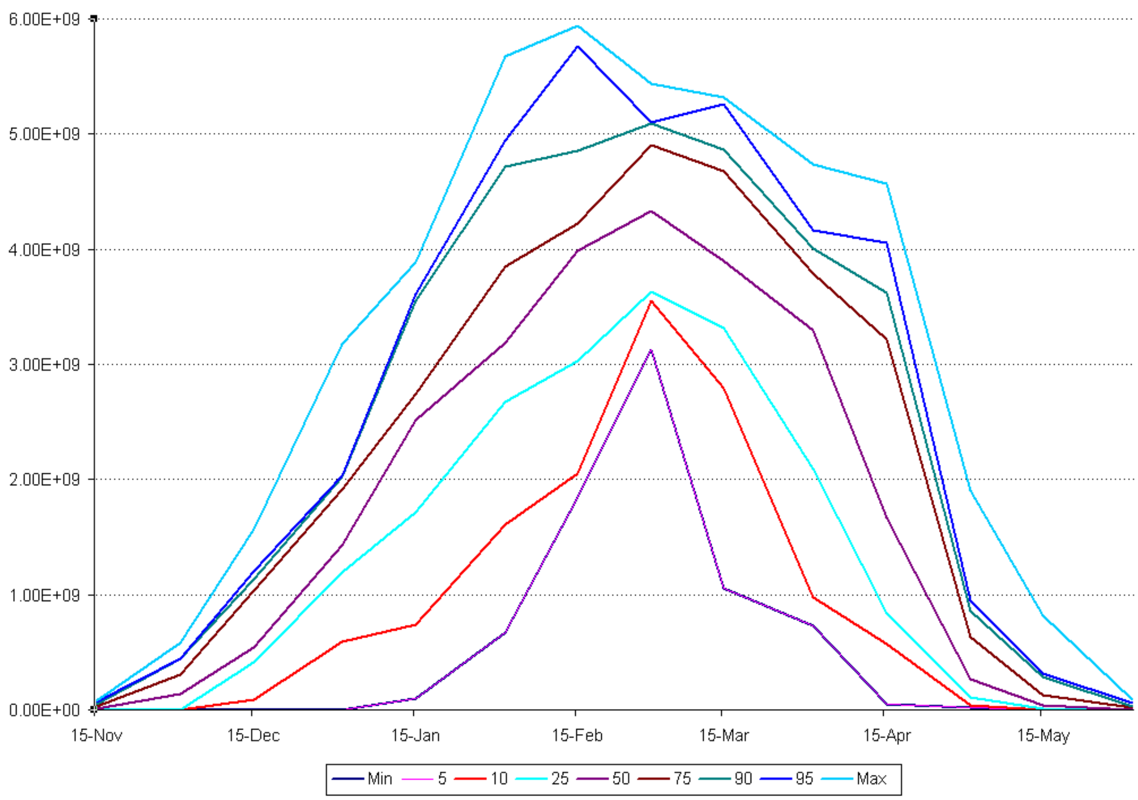

Figure 6. SWE percentiles for the Kajakai Reservoir watershed throughout the winter season determined on the 1st and 15th of each month.

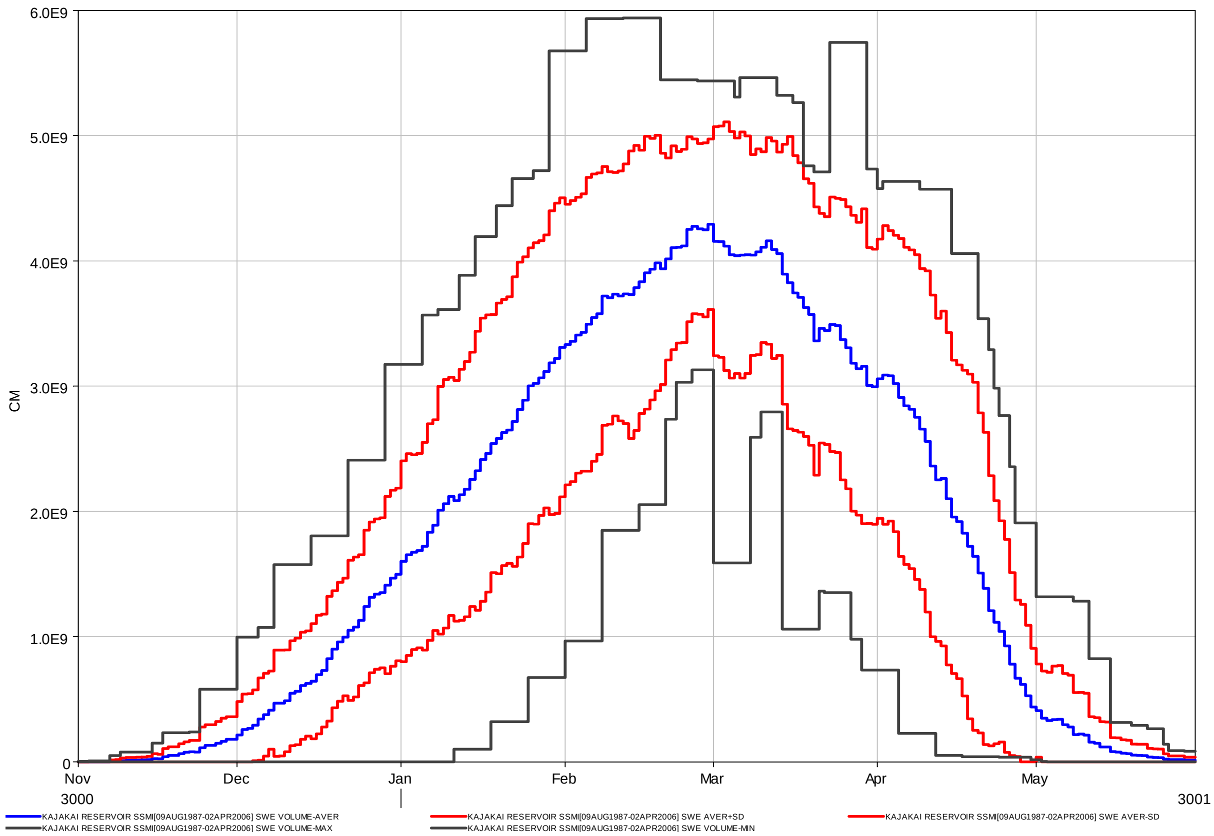

Figure 7. Daily average SWE (blue), average plus and minus one standard deviation (red), and maximum and minimum SWE (black) for the Kajakai Reservoir watershed throughout the winter season.

Table 7. SWE Percentiles based on SMM/I data of the Helmand watershed. The SWE volumes are given in $m^3 \times 10^9$.

	Percent of years with SWE volumes less than								
Date	**Min/0**	**5**	**10**	**25**	**50**	**75**	**90**	**95**	**Max/100**
15-Nov	0.000	0.000	0.000	0.000	0.010	0.032	0.053	0.075	0.079
1-Dec	0.000	0.000	0.000	0.002	0.144	0.326	0.464	0.483	0.706
15-Dec	0.000	0.000	0.095	0.431	0.607	1.205	1.210	1.309	1.972
1-Jan	0.000	0.000	0.629	1.490	1.834	2.514	2.774	2.848	4.663
15-Jan	0.106	0.106	0.819	2.070	3.289	4.525	4.768	5.506	6.910
1-Feb	1.007	1.007	3.206	3.742	5.431	6.844	8.331	8.521	8.900
15-Feb	2.619	2.619	3.606	4.925	6.084	7.848	9.265	9.463	11.846
1-Mar	4.395	4.395	4.684	5.459	6.437	7.315	9.339	9.875	10.583
15-Mar	2.441	2.441	3.733	3.974	5.451	6.071	7.982	9.342	9.370
1-Apr	0.797	0.797	1.141	2.782	4.113	4.991	5.444	5.778	6.086
15-Apr	0.054	0.054	0.658	0.920	2.049	4.036	4.567	5.274	5.666
1-May	0.017	0.017	0.038	0.112	0.328	0.715	0.978	1.373	2.324
15-May	0.000	0.000	0.000	0.007	0.046	0.142	0.347	0.392	0.927
1-Jun	0.000	0.000	0.000	0.000	0.000	0.021	0.028	0.056	0.097

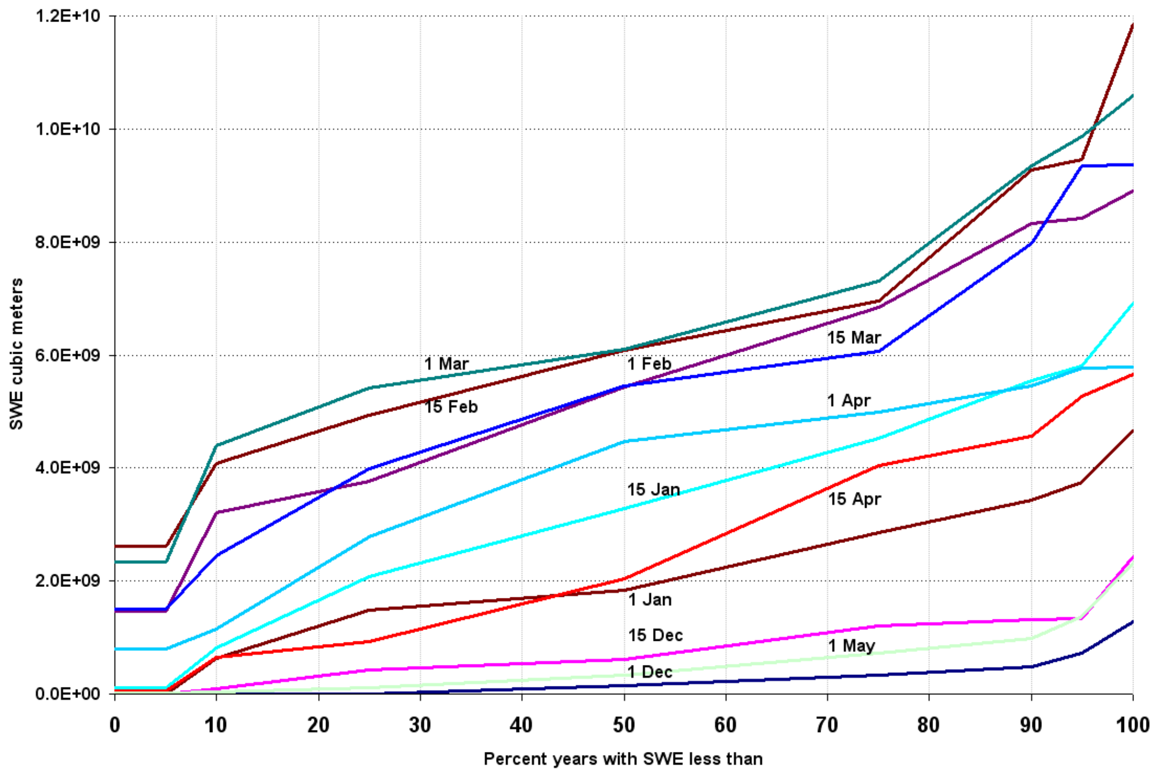

Figure 8. SWE percentiles for the Helmand watershed for given dates.

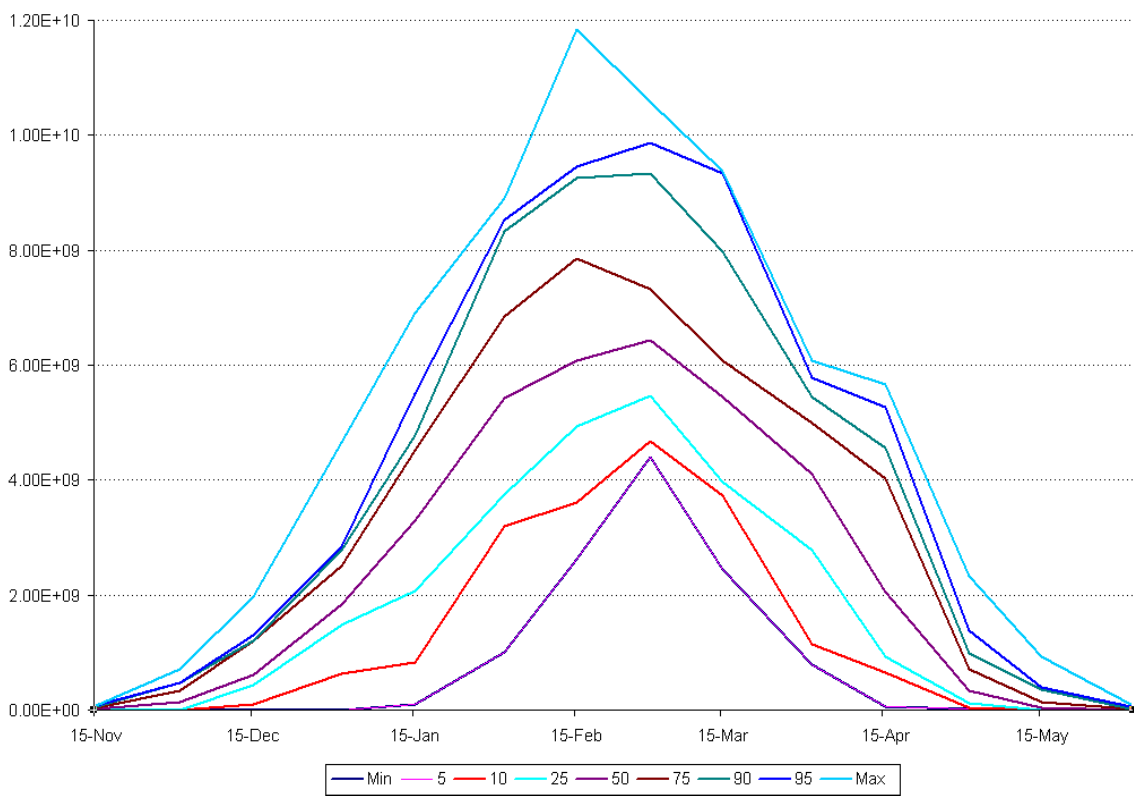

Figure 9. SWE percentiles for the Helmand watershed throughout the winter season determined on the 1st and 15th of each month.

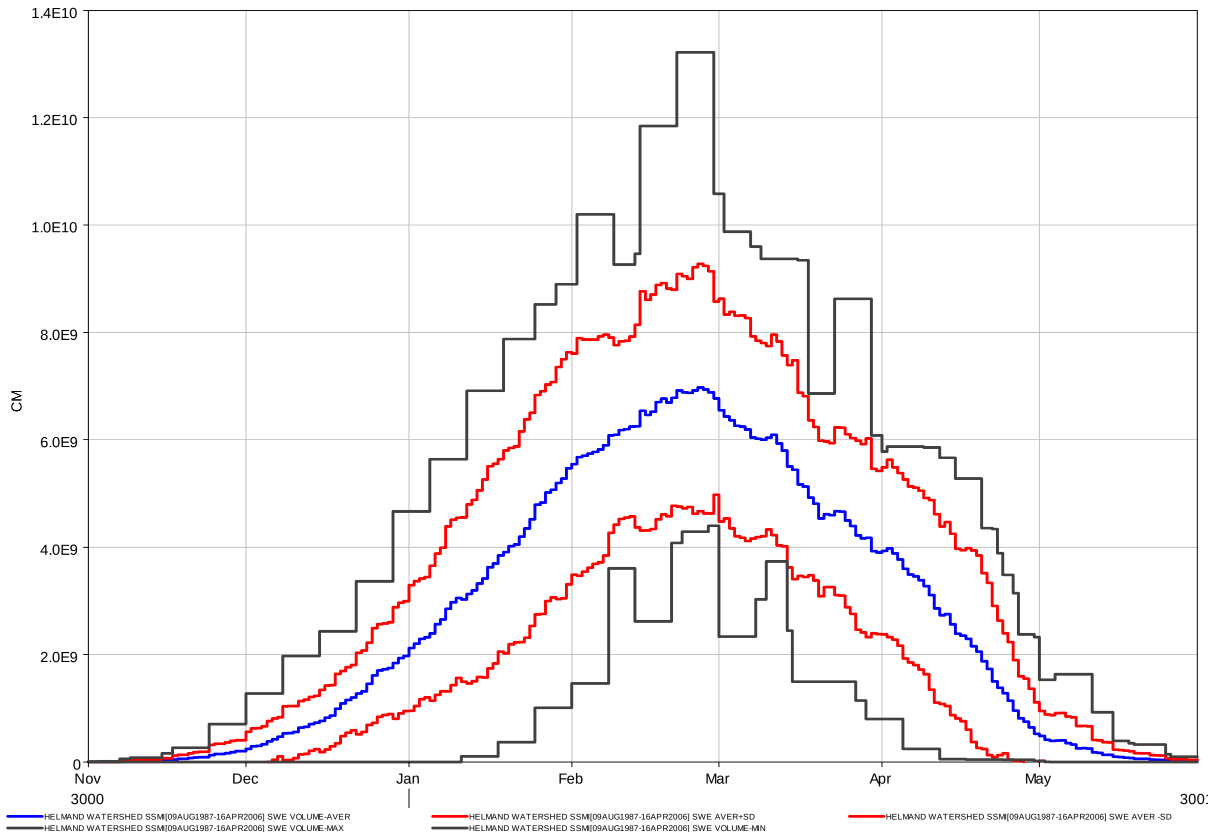

Figure 10. Daily average SWE (blue), average plus and minus one standard deviation (red), and maximum and minimum SWE (black) for the Helmand watershed throughout the winter season.

SMMR Data. As with the SMM/I data, the SMMR data resulted in a time series of SWE volumes for the watershed upstream of the Kajakai Reservoir and the entire Helmand watershed after the processing described above. Each SWE value represented the monthly average SWE detected in the month that began on the date associated with the SWE data value. The time series began in November 1978 and continued to July 1987. The monthly SSMR SWE results are shown in Figure 11. The maximum average monthly SWE detected each year is listed in Table 8. The annual statistics of the SMMR data were determined by analyzing the monthly SSMR data. The monthly SWE values were then analyzed using the *cyclic analysis* math function of DSSVUE. This determined the average, a range of percentiles, the standard deviation, the maximum, and the minimum for each month of the year. The values for the Kajakai Reservoir watershed are listed in Table 9, and the values for the entire Helmand watershed are listed in Table 10; the average monthly average SWEs are displayed in Figure 12.

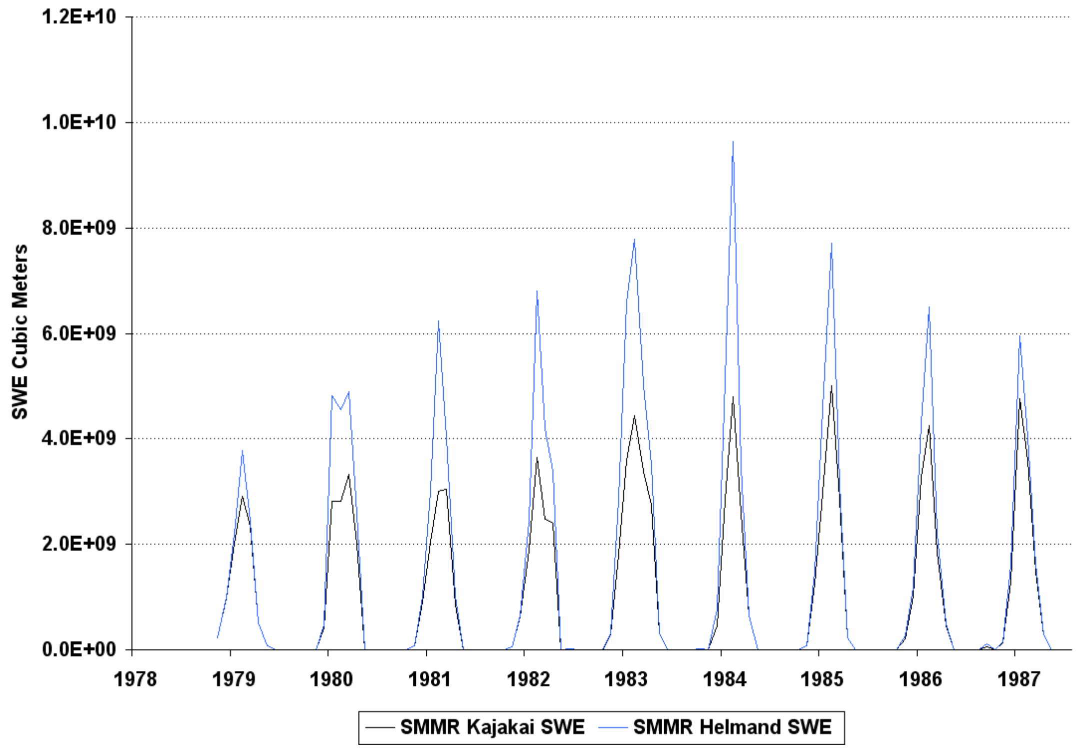

Figure 11. Time series of SMMR data.

Table 8. Maximum average monthly SWE detected each year based on SMMR data. The date given is the month in which the maximum average occurred.

Kajakai Reservoir		Helmand watershed	
Date	**SWE ($m^3 \times 10^9$)**	**Date**	**SWE ($m^3 \times 10^9$)**
Feb-79	2.907	Feb-79	3.773
Mar-80	3.332	Mar-80	4.897
Mar-81	3.035	Feb-81	6.238
Feb-82	3.645	Feb-82	6.806
Feb-83	4.450	Feb-83	7.781
Feb-84	4.799	Feb-84	9.636
Feb-85	5.005	Feb-85	7.717
Feb-86	4.255	Feb-86	6.497
Jan-87	4.762	Jan-87	5.945

Table 9. SWE percentiles based on SMMR data of the Kajakai Reservoir watershed. The SWE volumes are given in $m^3 \times 10^9$.

	Percent of years with SWE volumes less than								
Month	**Min/0**	**5**	**10**	**25**	**50**	**75**	**90**	**95**	**Max/100**
Nov	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.015	0.015
Dec	0.000	0.000	0.000	0.006	0.073	0.210	0.230	0.288	0.288
Jan	0.424	0.424	0.424	0.463	0.989	1.253	1.278	1.818	1.818
Feb	1.894	1.894	1.894	2.029	2.827	3.269	3.598	4.762	4.762
Mar	2.815	2.815	2.815	2.907	3.645	4.450	4.799	5.005	5.005
Apr	1.484	1.484	1.484	1.849	2.587	3.035	3.332	3.375	3.375
May	0.220	0.220	0.220	0.284	0.636	2.010	2.407	2.742	2.742
Jun	0.000	0.000	0.000	0.000	0.000	0.000	0.073	0.320	0.320
Jul	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.019	0.019

Table 10. SWE Percentiles based on SMMR data of the Helmand watershed. The SWE volumes are given in $m^3 \times 10^9$.

	Percent of years with SWE volumes less than								
Month	**Min/0**	**5**	**10**	**25**	**50**	**75**	**90**	**95**	**Max/100**
Nov	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.014	0.014
Dec	0.000	0.000	0.000	0.006	0.071	0.233	0.269	0.320	0.320
Jan	0.470	0.470	0.470	0.637	1.025	1.482	1.608	2.846	2.846
Feb	2.187	2.187	2.187	2.434	4.564	5.116	5.945	6.593	6.593
Mar	3.773	3.773	3.773	4.028	6.497	7.717	7.781	9.636	9.636
Apr	1.624	1.624	1.624	2.216	3.472	4.194	4.897	5.024	5.024
May	0.224	0.224	0.224	0.280	0.649	2.570	3.384	3.520	3.520
Jun	0.000	0.000	0.000	0.000	0.000	0.000	0.074	0.325	0.325
Jul	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.019	0.019

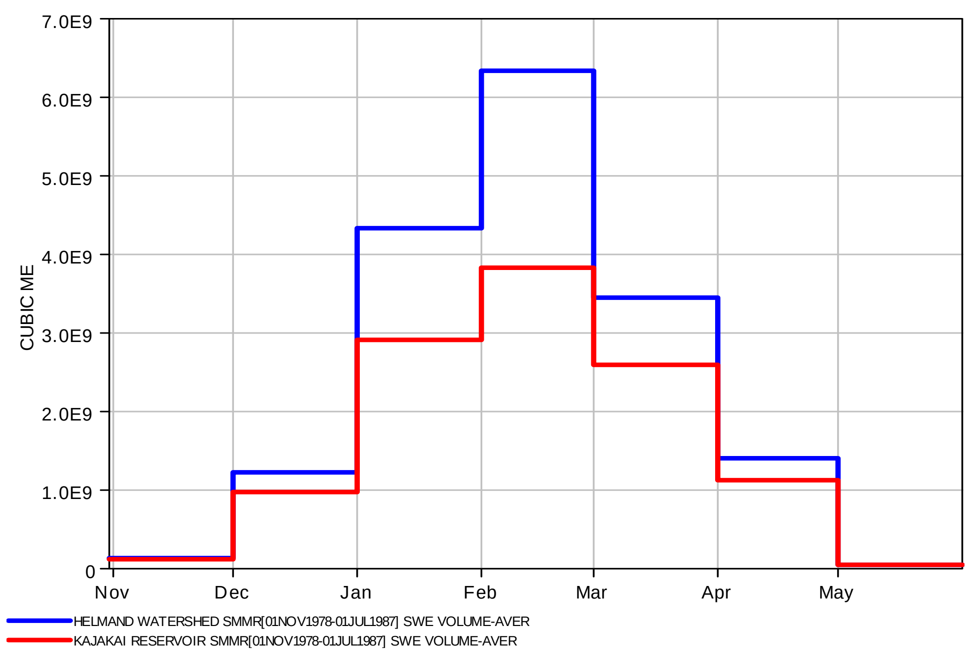

Figure 12. Monthly average of SMMR data.

Comparison of the SMM/I and SMMR data. It is difficult to compare the SMM/I and the SMMR data for a variety of reasons. The SMM/I data represented the maximum SWE detected in each pixel over a seven-day period, and the SMMR data represented the monthly average SWE. The time periods, during which each satellite collected data did not overlap, so the values cannot be compared directly. In fact, as noted above, NSIDC warns against directly comparing the two results. However, a simple comparison was done by comparing the annual statistics determined for each data set. In this case, the daily average SWE based on the seven-day maximum of the SSM/I data and the monthly average SWE based on the monthly average SSMR data are displayed in the same graph and shown in Figure 13. It can be seen that the averages from both satellites roughly agree and compare to each other as well as can be expected from two such different data sources.

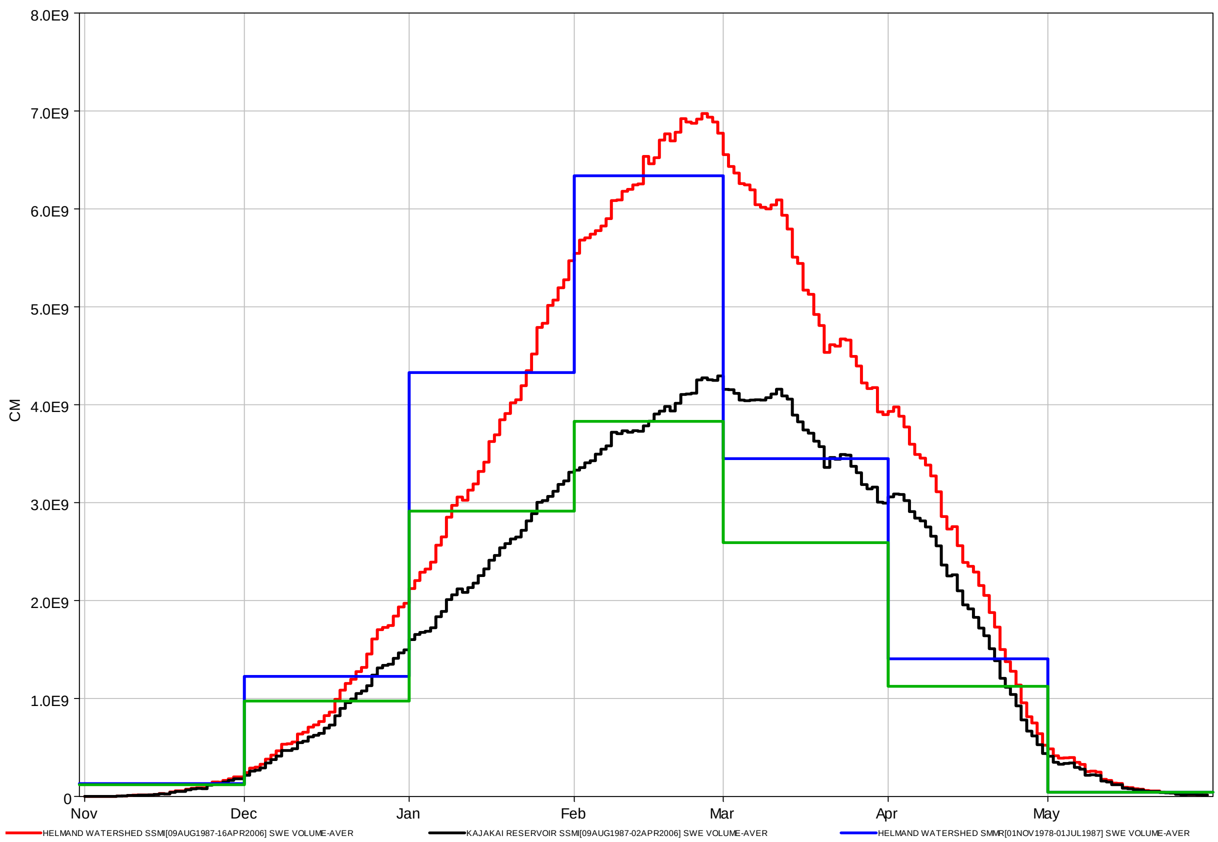

Figure 13. Average SWE volume throughout the winter. The data for the total Helmand watershed are shown in red and blue, and the data for the Helmand watershed upstream of Kajakai Reservoir are shown in black and green. The SMMR monthly data 1978-1987 are shown in blue and green, and the SMMI weekly data converted to daily, 1987-2006, and shown in red and black.

Summary

This report describes the analysis of satellite-derived SWE data for the Kajakai Reservoir watershed and the Helmand River watershed. Two satellites were used: the Special Sensor Microwave/Imager (SSM/I), one of several sensors carried on Defense Meteorological Satellite Program (DMSP) satellites, and the Scanning Multi-channel Microwave Radiometer (SMMR). SSM/I data are available weekly over the Helmand Reservoir from the winter 1987-88 through the present; and the SMMR data are available monthly for the period 1978-1987. The satellite data were analyzed using GIS techniques to determine the total SWE volumes in the two watershed areas. This analysis produced a time series of SWE. In the case of the SSM/I data it was a weekly time series with the data representing the maximum SWE detected during the seven-day period; in the case of the SMMR data it was a monthly time series of monthly average SWE. The data from each watershed were analyzed and compared. The annual statistics of each were also determined for both data sets.

Acknowledgements

The continuing and long-term assistance by MaryJo Brodzik of the National Snow and Ice Data Center is gratefully acknowledged.

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Knowles, K., E. Njoku, R. Armstrong, and M.J. Brodzik (2002) *Nimbus-7 SMMR Pathfinder daily EASE-Grid brightness temperatures*. Boulder, CO: National Snow and Ice Data Center. Digital media and CD-ROM.

U.S. Army Corps of Engineers (2006). *HEC-DSSVue introduction.* Davis, CA: Hydrologic Engineering Center. http://www.hec.usace.army.mil/software/hec-dss/ hecdssvue-dssvue.htm.

Appendix C – Draft Reservoir Regulation Manual for Kajakai Reservoir

1. General Objectives

The objective of the Water Control Plan is to define reservoir regulation procedures and practices used for regulating storage within and releases from the Kajakai Reservoir in accordance with authorized uses and priorities.

2. Overall Water Control Plan

The Kajakai Dam was constructed in the early 1950s. The original purpose of the Kajakai reservoir was for irrigation supply and flood protection. Power generating capabilities were added later. At present, the reservoir is primarily operated to meet irrigation demands. To the greatest extent possible flows are released to maximize power production within the operation for irrigation supply and flood control.

The Water Control Plan for Kajakai Reservoir is divided into 3 parts, (1) Conservation Release, (2) Drawdown, and (3) Flood Control and Refill. The plan is summarized in the Water Control Diagram, Plate 1.

The first priority in all parts of the year is to release to meet the minimum irrigation and treaty flow requirements. These minimum flows are summarized in Table 1.

Table 1. Monthly Demands from Kajakai Reservoir.

Month	Helmand Province (Upper Helmand)	Nimroz Province (Lower Helmand)	Iran Treaty	Total
	cms	cms	cms	cms
Jan	68.1	89.0	34.7	191.8
Feb	0.0	95.9	78.2	174.1
Mar	83.7	110.7	73.1	267.5
April	99.4	115.8	31.1	246.3
May	103.2	116.0	9.0	228.2
Jun	97.5	100.6	19.7	217.8
Jul	89.6	85.1	13.7	188.4
Aug	93.0	68.2	9.4	170.6
Sep	89.2	60.5	2.3	152
Oct	71.75	69.9	5.0	146.65
Nov	72.2	79.1	12.7	164
Dec	89.7	86.1	23.0	198.8
Total	**957.35**	**1,076.9**	**311.9**	**2,346.15**

Table 2 summarizes the minimum outflow from Kajakai Reservoir. The minimum flows are based on the demands summarized in Table 1 and account for minimum outflow from Dahla Reservoir.

Table 2. Minimum Outflow from Kajakai Reservoir by Month

Month	Minimum Outflow
	cms
Jan	179.2
Feb	166.4
Mar	252.0
April	229.1
May	210.7
Jun	202.0
Jul	174.5
Aug	157.7
Sep	140.1
Oct	135.4
Nov	152.0
Dec	184.8
Total	**2,183.9**

The minimum outflows from Kajakai Reservoir are to be met as long as there is storage in the reservoir above elevation 995.0 m. unless reduced releases have been coordinated. See Section 3. Water Supply/Irrigation and Section 6. Drought Contingency Plan.

a. Conservation Release Season. In the Conservation Release Season (16 May to 15 November) regulation will be to release the minimum outflow requirement and maintain the reservoir elevation as close as possible to the Maximum Conservation Pool Elevation of 1045.0 m. The release will be the minimum outflow requirement or the flow needed to keep the reservoir at elevation 1045 m., whichever is more.

b. Winter drawdown season. In the Winter Drawdown Season (16 November to 31 January) the operation will be to release the minimum outflow requirements and draft the reservoir to provide space to control late winter and spring floods. Beginning at midnight on 15 November the reservoir will be drafted at a constant rate to reach elevation 1036.0 m by 31 December. In most years the minimum outflow requirements will have the reservoir drafted well below the Water Control Diagram by 15 November. The drawdown rate of the reservoir can be adjusted as needed to reach the target elevation of 1036 meters on 31 December.

After 31 December the reservoir can remain at elevation 1036 m through 31 January. Depending on snow water equivalent (SWE) conditions on 1 February, target elevations for 1 March have been established to provide flood control space and increase the probability of refill. Three target elevations below elevation 1036 have been identified and are shown on the water control diagram Plate 1. These target elevations are summarized in Table 3.

Table 3. Kajakai Reservoir Target Elevation for 1 March SWE Conditions In Helmand Watershed

Snow Water Equivalent on 01 February	Reservoir Target Elevation for 01 March
m^3	**m**
$<2.0*10^9$	1036.0
$2.0\text{-}3.0*10^9$	1030.0
$3.0\text{-}4.5*10^9$	1025.0
$>4.5*10^9$	1020.0

c. Flood Control and Refill Season. In the Flood Control and Refill Season (01 February to 15 May) the operation will be to release the minimum outflow requirements. In February the objective will be to maintain flood control space and draft the reservoir by 1 March to the elevation indicated by the SWE levels. Refill to the maximum conservation pool elevation of 1,045 m will begin in March depending on the 01 March target elevation as summarized in Table 4 and shown on the Water Control Diagram Plate 1.

Table 4. Kajakai Reservoir Scheduled Date to Begin Refill

Reservoir Target Elevation for 01 March	Scheduled Date to begin Refill
m	
1036.0	01 March
1030.0	15 March
1025.0	31 March
1020.0	31 March

The scheduled date for the reservoir to be full to the maximum conservation pool is 15 May.

3. Water Supply/Irrigation

The main water supply requirements for flow in the Helmand River consist of irrigation demands in the Helmand Valley below Kajakai and flow requirements to Iran under an international agreement (per 1979 WAPCOS report). Irrigation and treaty flow requirements are summarized in Table 1.

Table 2 summarizes the minimum outflow from Kajakai Reservoir. The minimum flows are based on the demands summarized in Table 1 and account for minimum outflow from Dahla Reservoir. Releases for irrigation will be made from the irrigation discharge structure which has three control valves. The combined capacity of the irrigation outlet is summarized in Table 5.

Table 5. Kajakai reservoir composite irrigation outlet capacity – irrigation valves.

Elevation (m)	Maximum Release (cms)
970.0	0.0
980.0	63.8
990.0	127.5
1000.0	150.1
1010.0	172.8
1020.0	192.6
1030.0	212.5
1033.5	228.2
1040.0	233.7
1045.0	240.1

The minimum outflows from Kajakai Reservoir are to be met as long as there is storage in the reservoir above elevation 995.0 m. unless reduced releases have been coordinated.

The Iranian treaty minimum flow requirements are based on flow measured at Dehwa Rud gauging station upstream of Kajakai Reservoir and therefore these minimum flow requirements are added to the total release requirement for Kajakai Reservoir. The treaty contains a provision that upon determination of whether the mean March flow is above or below the historical amount stated in the treaty (73.1 cms) the treaty flow for the rest of the ensuing year may be reduced proportionately (base on the ratio of the actual observed March flow divided by 73.1 cms). For example if the March inflow to Kajakai is determined to be 60 cms, then the monthly treaty flow requirements for the remainder of the year may be reduced by a factor of 60/73.1 = 0.82. The April treaty requirement would then be 31.1 cms * 0.82 = 25.5 cms. The minimum reservoir outflow for April would be reduced by 5.6 cms (31.1-25.5). This process would be used to adjust minimum outflows for the remaining months of the year.

4. Flood Control

Floods in the Helmand River Basin generally occur as a result of rain and snowmelt in March, April and May. The Water Control Diagram presented in Plate 1 allows for a variable target reservoir elevation in the winter depending on SWE conditions. The target elevation for 1 March is set based on the SWE in the watershed above the reservoir on 1 February. The reservoir elevation will often be lower than the elevation indicated by the diagram after minimum outflow requirements are satisfied. The variable target elevation balances the flood risk with the risk of not filling the reservoir. With a higher SWE the flood risk would be higher and the reservoir would be drafted to a lower elevation to provide more space for flood control. With a lower SWE the flood risk would be lower and a lesser amount of storage space in the reservoir would be needed for flood control.

There are no known constraints defined downstream of the reservoir such as flood regulation goal flows, bankfull flows or flood stages. As such, flood control operation is to maintain the minimum project outflow unless the inflow and pool elevation indicate the use of the Special Flood Regulation Curves in Plate 2. The Special Flood Regulation Curves allow operators to better manage a flood event using the reservoir storage above the spillway crest.

The outlet capacity of the spillway is shown in Table 6.

Table 6. Kajakai reservoir outlet capacity – spillway.

Elevation (m)	Maximum spillway release (cms)
1036.0	0.0
1039.75	1000.0
1041.93	2000.0
1043.76	3000.0
1045.38	4000.0
1046.86	5000.0
1048.24	6000.0
1049.55	7000.0
1050.0	7500.0

5. Hydroelectric Power

The powerhouse at Kajakai Dam consists of two 16.5 MW units and space for a third unit. The outlet capacity of the power plant is shown in Table 7. Power generation at the Kajakai Project is dependent on upon the releases for other purposes. To the greatest extent possible releases from the project will be used to generate power.

Table 7. Kajakai reservoir outlet capacity – power plant.

Elevation (m)	Existing turbines (cms)
1008.0	71.0
1018.0	78.5
1028.0	85.3
1038.0	91.7
1040.0	92.9
1045.0	89.5
1048.0	86.9

6. Drought Contingency Plan

To ensure a water supply from the reservoir throughout the Conservation release season, it may be desirable to scale back water use and reservoir releases in years with lower stream flow. A brief analysis of flow and snow water equivalent data indicates that in years of average SWE or greater on 1 March there will be adequate flow to meet the full downstream flow requirements in Table 1. In years when SWE is less than average on 1 March a reduction in downstream water use and reservoir minimum releases should be considered to ensure a water supply throughout the Conservation release season. Table 8 summarizes suggested reductions in reservoir releases for 1 March SWE data.

Table 8. Multiplication Factor for Minimum Reservoir Releases from Kajakai Reservoir based on 01 March SWE Conditions in Helmand Watershed

Snow Water Equivalent on 01 March	Factor for Minimum Reservoir releases March through October
m^3	
$>4.3*10^9$	1.00
3.5 to $4.3*10^9$	0.75
1.8 to $3.5*10^9$	0.50
$<1.8*10^9$	0.25

Reductions in reservoir releases need to be coordinated with downstream water users.

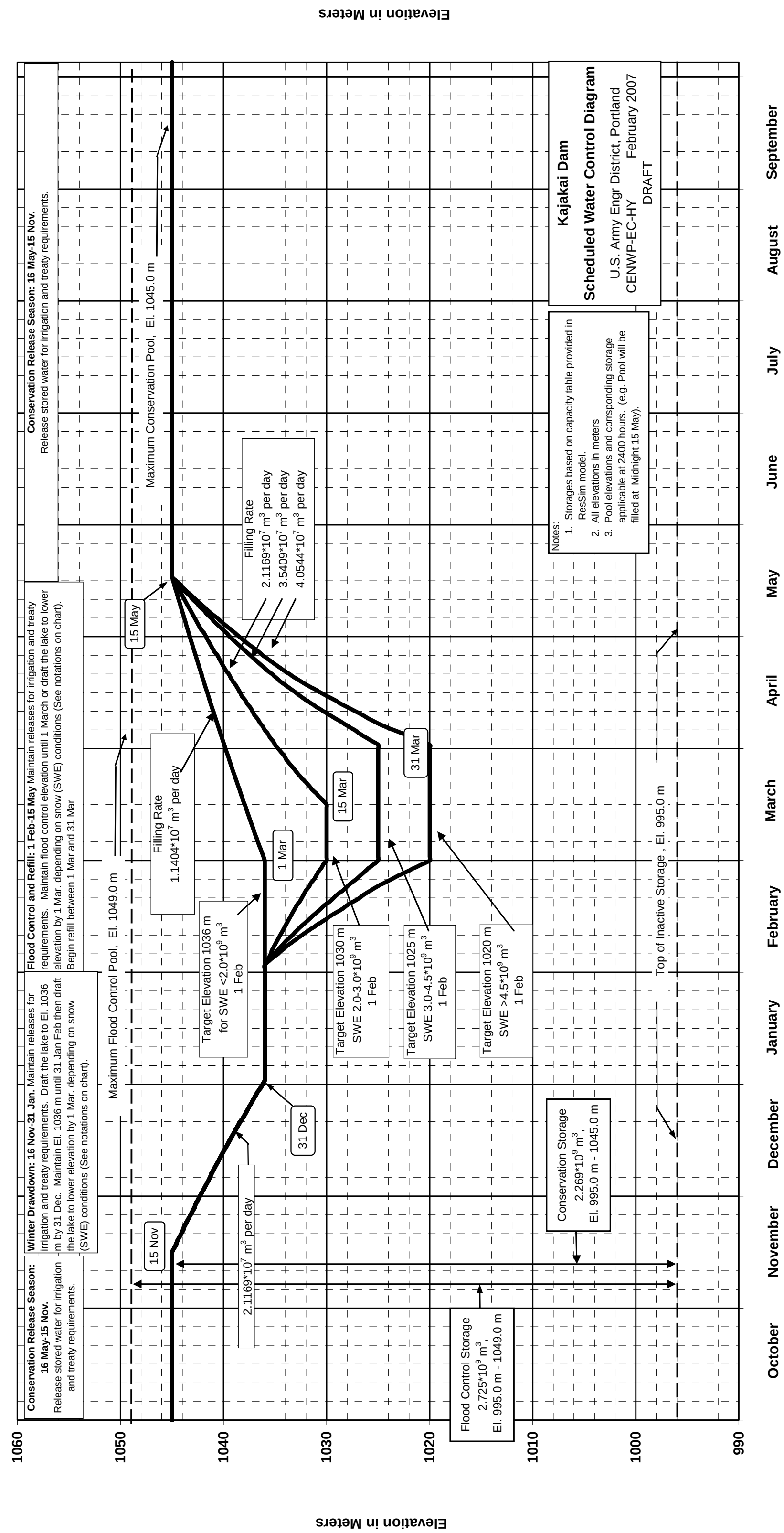

Plate 1. Water Control Diagram

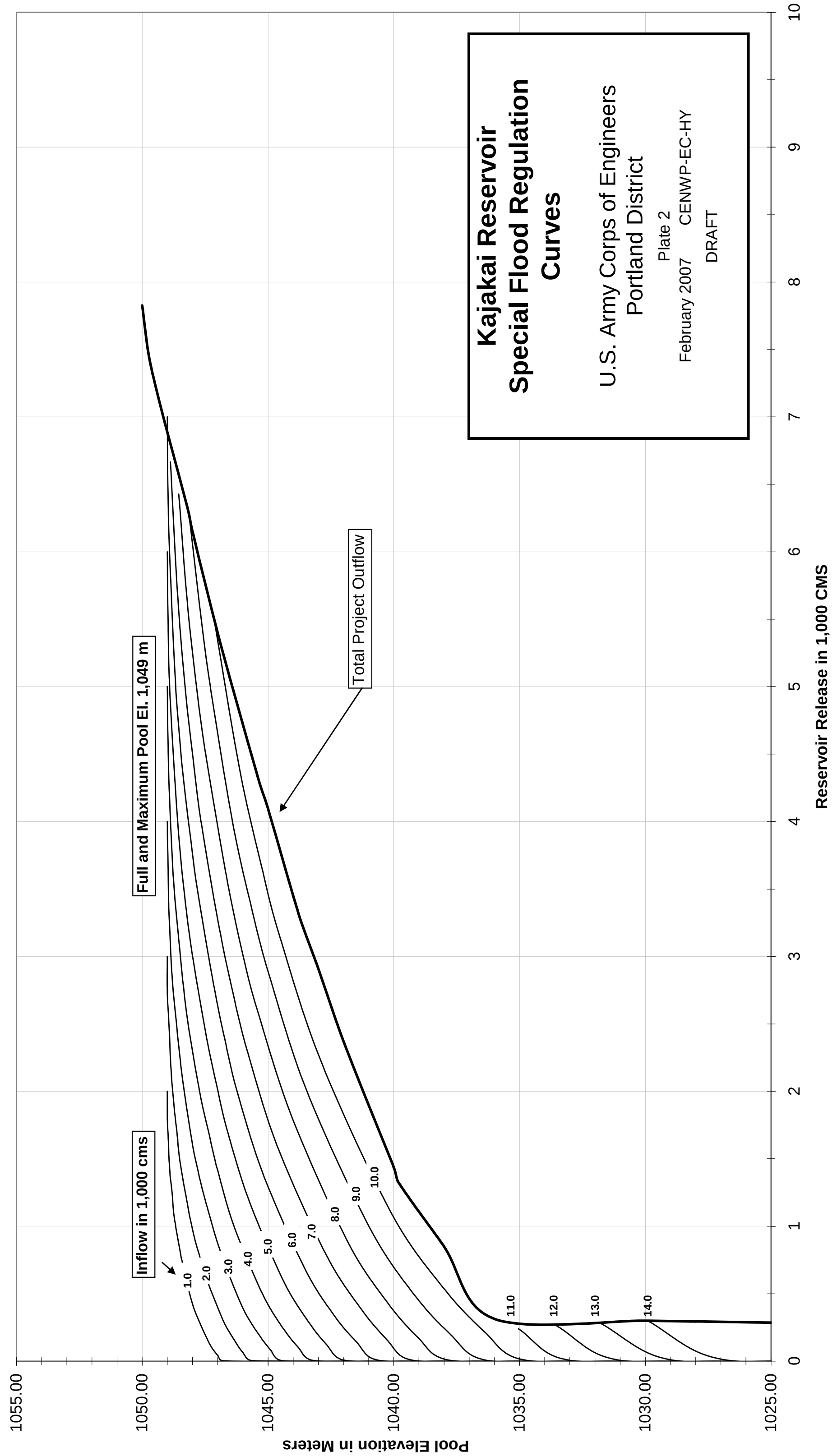

Plate 2. Special Flood Regulation Curves