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Using Acoustic Doppler Velocity Measurement Techniques to Quantify Hydraulic Characteristics of Interflows in Lake Mead

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1. Abstract

Acoustic velocity measurement techniques have advanced significantly in recent years and are useful for studying stratified flows in reservoirs. This paper describes the use of these instruments to study an interflow in Lake Mead - the reservoir formed by Hoover Dam. This interflow consists of treated wastewater effluent and contaminated groundwater which has the potential to impact the city of Las Vegas' municipal water supply. The purpose of this study was to determine the characteristics of this interflow including its velocity profile, horizontal and vertical extent, and travel time to a municipal water intake. Acoustic Doppler current profiler (ADCP) transects were used to determine the horizontal and vertical extent of the interflow by using suspended particles (acoustic scatterers) as an indicator of the interflow. An Acoustic Doppler velocimeter (ADV) was used to measure the interflow's velocity profiles at several locations. This study was done in combination with limnological sampling of Lake Mead. The combination of these two studies will result in a very thorough description of the hydraulics and water quality characteristics of the interflow.

2. Introduction

Reclamation conducted a series of limnological investigations of the Boulder Basin of Lake Mead beginning in July 1990 and continuing monthly thereafter (LaBounty and Horn, 1997). The purpose of the study is to: 1) collect trend data on the influence of the wastewater and other drainage from the Las Vegas Basin via Las Vegas Wash into Lake Mead; 2) investigate the status of the limnological conditions of Boulder Basin as a source of supply for drinking water; 3) perform research into new technology for evaluating limnological features, in particular those related to water quality conditions of reservoirs; and 4) contribute to understanding the ecology of Lake Mead as it relates to the operational scheme of the Colorado River system

Lake Mead is a mainstem Colorado River reservoir in the Mohave Desert, Arizona-Nevada . Its lower end is 15 km east of Las Vegas, Nevada. Lake Mead, formed in 1935 following construction of Hoover Dam is the largest reservoir in the United States by volume (36.7×10^9 m^3) and is second only to Lake Powell in terms of surface area (660 km^2). The Colorado River contributes about 98 percent of the annual inflow to Lake Mead; the remaining three inflows, the Virgin and Muddy Rivers and Las Vegas Wash, provide the remainder. Annual inflow via Las Vegas Wash is currently about 1.9×10^8 m^3 and provides the second highest inflow volume to Lake Mead. Discharge from Hoover Dam is hypolimnetic and occurs 83 m below the maximum operating level of 364 m above msl. Hoover Dam's annual discharge is approximately 9×10^9 m^3. Annual withdrawal through the Southern Nevada Water System's municipal intake in Boulder Basin is presently about 0.55×10^9 m^3 (Roefer et al. 1996).

As with other reservoirs, dam operations have a great influence on Lake Mead's water quality and ecology (Thornton 1990). Typically, the hydrodynamics of such large reservoirs are complex and not well understood. Each basin within Lake Mead is ecologically unique and responds differently to the inflow-outflow regime. Furthermore, different sources of water entering Lake Mead, as in other reservoirs, often retain their identity and influence for substantial distances into the reservoir and do not necessarily mix completely with the rest of the water column (Ford 1990). This can lead to significant underestimates of water retention time, transport rates, and fate of materials transported into the reservoir.

Boulder Basin is the most downstream basin and collects the combined flows from the reservoir's two main arms. Additionally, it receives all drainage from the Las Vegas Valley via Las Vegas Wash which discharges into Las Vegas Bay. This drainage includes both non-point surface and groundwater discharges as well as treated effluent from municipal wastewater treatment facilities. Boulder Basin is 15 km wide from Boulder Canyon to Hoover Dam (Black Canyon) and the distance from the confluence of Las Vegas Wash to Hoover Dam is approximately 16 km. The historical Colorado River channel lies along the eastern side of the basin.

The morphology and hydrodynamics of Lake Mead are such that the nutrient loading, as a result of discharges through Las Vegas Wash, is confined to Boulder Basin (Paulson and Baker 1981, Prentki and Paulson 1983). The seasonal hydrodynamics of the interflow created by Las Vegas Wash inflows are described in detail by LaBounty and Horn (1997). Boulder Basin serves as the primary source of drinking water for the Las Vegas Valley which includes nearly 1.5 million people. Water from Lake Mead serves nearly 25 million downstream users. In addition, the reservoir is the major outdoor recreation feature of the Lower Colorado River and is visited by millions of people each year.

3. Sampling Methods

Acoustic Doppler velocity measurements were collected during a regular site visit by Reclamation limnologists. The velocity profiling program was designed to examine the characteristics of the Las Vegas Wash interflow (plume) entering Lake Mead. Sampling locations were limited to Las Vegas Bay and Boulder Basin. Detailed sampling station descriptions and locations, as well as analytical methods used by the Lower Colorado Regional Laboratory for sample analysis, are available in a report by Holdren et al. (1998).

Velocity measurements were collected using an RD Instruments ADCP and a Sontek ADV. Velocity profile data were collected using both instruments at the same sites visited by the limnologists. Duplicate measurements were required because the ADCP is limited in its ability to measure low velocities, whereas, the ADV does not have this limitation.

3.1 ADCP measurements - Data were collected using an RD Instruments broadband ADCP, operated from both a stationary and moving boat. The ADCP uses the Doppler shift principle to measure velocities along four acoustic beams projected downward below the moving boat. The instrument sends out precise acoustic pulses and then receives backscattered acoustic signals reflected off of acoustic scatterers in the water column (e.g., organic or inorganic particles). The Doppler shift of the backscattered signal is proportional to the velocity of the particles. The beams diverge both longitudinally and laterally, as shown in figure 1, so that the velocity reported by the instrument is an average of measurements made along each of four different acoustic beams. Individual velocity measurements are made within discrete vertical depth cells, or bins, with a height of 100 centimeters each, yielding a velocity profile from near the surface to near the bed. Velocities cannot be measured near the surface because the transducer must be submerged and there is some time delay between the send and receive modes of operation. Velocities also cannot be measured very near the bed (approximately the last 10 percent of the depth) due to a phenomenon called side-lobe interference. Three orthogonal components of velocity are measured; an internal compass allows the velocities to be referenced to an Earth coordinate system (east/north/up). Tilt sensors are used to correct for any pitch/roll errors in depth measurements. In addition to the velocity data, the ADCP depth measurements can be used to determine the bathymetry along the transect. Dedicated bottom tracking pings are collected to track the motion of the ADCP relative to the channel bottom using the same Doppler shift

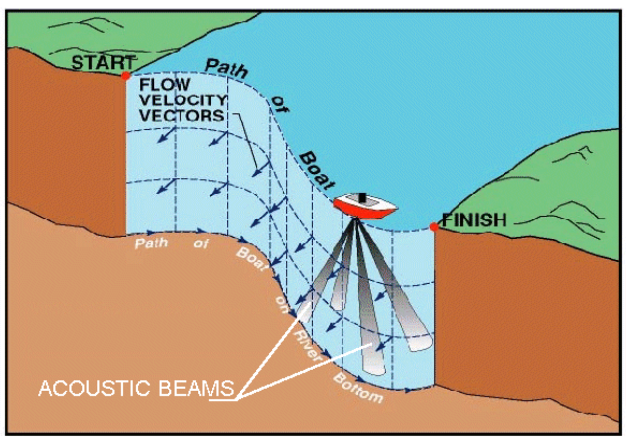

Figure 1. Typical acoustic beam configuration for a boat-mounted ADCP transect.

technique used to measure velocity. This measurement allows the water velocity measurements to be corrected for the relative boat motion, and permits tracking the position of the instrument during a transect. A more detailed description of ADCP operation can be found in RD Instruments' primer on ADCP technology (RD Instruments 1989).

The ADCP used for this work was a 300 kHz system which is best suited for this deep water application. Reclamation also uses ADCP's with 600 kHz and 1200 kHz transducer heads for shallow water applications, such as rivers or shallow reservoirs.

3.2 Acoustic Doppler Velocimeter (ADV) Measurements - ADVs use Doppler techniques to simultaneously measure three velocity components (u, v, and w) of flowing water from a single sampling volume. The ADV sampling volume is located 5 cm (2 in.) below the probe head and is cylindrical in shape (the probe volume is less than 0.25 cm^3). The profiling method involved lowering a 23 kg lead sounding weight, which contained the ADV probe (figure 2), to below the Las Vegas Wash interflow. Once the weight was in position, a 30-second sample at a frequency of 25 Hz was collected for a total of 750 velocity measurements. Next, the sounding weight was winched up a distance of 1m and another set of data were collected.

Typically, when the sounding weight system is used in flowing water the fins orient the ADV probe's x-axis parallel to the flow direction. For this application, the current was not sufficient to keep the probe oriented into the flow. As a result, it was not possible to determine the direction of the water currents using this ADV (this probe was not equipped with a compass). Only the speed of the horizontal currents could be determined. For future work, this limitation will be overcome by using an ADV equipped with a compass.

Figure 2. Photo of ADV and sounding weight.

4. Reservoir Operations

Lake Mead's water surface elevation for the two days of data collection was 368.0 m (1207.4 ft). Average daily flows in Las Vegas Wash at USGS gaging station 9419790 were 6.3 m^3/sec (222 ft^3/sec) on Aug. 2 and 6.2 m^3/sec (218 ft^3/sec) on August 3, 1999. The average daily releases from Hoover Dam were 405 m^3/sec (14,300 ft^3/sec) on August 2 and 532 m^3/sec (18,800 ft^3/sec) on August 3, 1999. Flows through the SNWS pumping plant at Saddle Island were about 12 m^3/sec (420 ft^3/sec) on August 3, 1999. A total of 8 pumps were running which is about half of the plant's total capacity.

Another important hydrologic event that is relevant to this study was a flash flood that occurred prior to this field work. On July 8, 1999, the Las Vegas Valley experienced a heavy rainfall event that resulted in flash flooding in Las Vegas Wash. The Clark County Regional Flood Control District reported this flood to be a 125-year recurrence interval flood. The maximum flow rate in the Wash was estimated to be 450 m^3/sec (16,000 ft^3/sec). This flood carried a large amount of debris and sediment into Las Vegas Bay.

It is important to note that the hydrodynamic characteristics of the Las Vegas Wash interflow moving into Las Vegas Bay are primarily a function of the Las Vegas Wash inflows (LaBounty and Horn, 1997). To a lesser degree, the flows through the SNWS pumping plant and Hoover Dam may influence the interflow characteristics. As a result, the findings from this field trip are applicable only for this set of flow conditions and reservoir stratification.

5. Results

The ADV and ADCP were used to collect both velocity profiles and transects, respectively, at many locations in Las Vegas Bay. The sampling stations were located 1.5, 1.8, 2.15, 2.6, 3.5, 4.15, 4.95, and 7.3 river miles from the Las Vegas Bay inlet. These sites are identified with a LVB (Las Vegas Bay) prefix.

Both the ADV and ADCP report an acoustic backscatter signal strength which was used to detect turbidity plumes and other scatterers in the water column. When a layer of water contains a large number of scatterers, the amplitude of the backscattered signal increases. The acoustic backscatter intensity was used to locate the interflow both vertically and horizontally throughout Las Vegas Bay. The ability to detect the typical Las Vegas Wash interflow was complicated because of a second plume associated with an earlier flash flood in Las Vegas Wash. At profiling locations upstream from LVB2.15, the flood plume and the Las Vegas Wash interflow were nearly coincident. Likewise, decaying organic particles and fine clays can accumulate within the density gradient associated with the thermocline. These particles will also generate high backscattered signals. All these factors combined to make isolating the Las Vegas Wash interflow a challenge.

5.1 ADV Profiles - The ADV data were the most accurate speed measurements collected inside the interflow. At each sampling depth two values were collected: the speed and the signal amplitude. The maximum signal amplitudes corresponded very closely with peak specific conductance values collected by the limnologists (figure 3). Speeds inside the interflow varied from 4.5 to 14.2 cm/sec. In general, the speeds decreased with distance from Las Vegas Wash. Small variations in current speeds from station to station were detected and resulted from waves and wind and the boat motion they create. When possible, the boat was anchored to minimize this motion, but rotation around the anchorage, caused by the wind or boat motion caused by waves, could not be prevented.

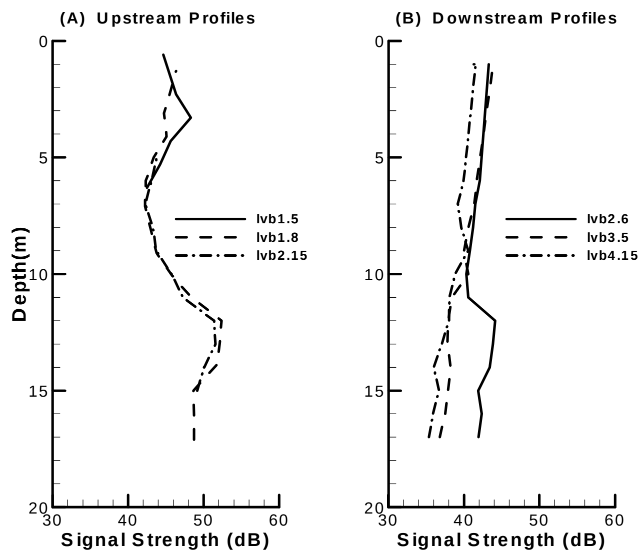

Figure 3. Profiles of ADV acoustic signal strength for six sampling sites in Las Vegas Bay.

5.2 Interflow Location - Using the amplitude of the ADV signal strength, the vertical extent of the interflow could be determined. Figure 3 shows the profiles of signal strength measured at sites LVB1.5, LVB1.8, LVB2.15, LVB2.6, LVB3.5 and LVB4.15. The interflow was located about 13 meters deep from station LVB1.8 to LVB2.6. Further into Las Vegas Bay, the interflow was centered about 10 meters deep. It was also apparent that the particles in the plume were settling out because the amplitude of the ADV signal was decreasing with distance traveled into Las Vegas Bay. The typical thickness of the interflow was about 4 to 5 meters. The interflow location and flood plume were also quantified by August 2, 1999 using specific conductance profiles collected by Reclamation limnologists. Remnants of the flash floods were detected at greater depths. Conductivity profiles were collected in front of the SNWS intake on July 16, 1999 (eight days after the flood) showed a strong plume located between 11 and 16 meters deep (Roefer 1999).

5.3 Interflow Travel Times - The ADV data were used to compute interflow travel times between sampling stations LVB1.5, LVB1.8, LVB2.15, LVB2.6, LVB3.5, and LVB4.15. The travel times (in hours) were calculated by dividing the number of river miles between stations by the average of the maximum interflow speeds measured at the two stations. Using an average interflow speed of 0.15 miles per hour, the travel time between LVB4.15 to LVB4.95 was computed to be 5.5 hours. Using an interflow speed of 0.15 miles per hour the travel time between LVB4.95 to LVB7.3 was computed to be 14.2 hours. Similarly, using a speed of 0.15 miles per hour, the travel time between LVB7.3 to SNWS Pumping Plant intake was estimated to be 13.5 hours. For this specific set of hydraulic conditions, the estimated travel time from LV1.5 to the SNWS pumping plant was about 49.5 hours. A similar travel time for the July 8, 1999 flood plume (~53 hours) was determined from records of turbidity in SNWS Intake raw water samples (Roefer

1999).

5.4 ADCP Transects - ADCP transects were used to determine the lateral extent of the Las Vegas Wash interflow as it passes through Las Vegas Bay and into Boulder Basin. Transects were made by collecting ADCP data on a boat that was traversing from right bank to left bank or vice versa. In general, an ADCP profile was collected for every 2 to 3 meters of boat travel or once every 3 to 5 seconds. Both of these values will vary with boat speed and water depth. The ADCP signal strength was used in this study to determine the position of the interflow both vertically and horizontally throughout Las Vegas Bay. The ability to detect the typical Las Vegas Wash interflow was complicated because of a second plume associated with earlier flash floods in Las Vegas Wash. At many profiling locations the flood plume and the typical Las Vegas Wash interflow were nearly coincident. This was especially true at sampling sites closer to the Las Vegas Wash delta. At locations beyond LVB7.3, detecting the Las Vegas Wash interflow was difficult because we could not determine if the particles were organic (from the reservoir) or were from Las Vegas Wash because the limnologists were unable to detect the interflow with their specific conductance probe. ADCP signal strengths and specific conductance measurements were both good methods for detecting the Las Vegas Wash interflow. However, the ADCP cannot differentiate between particles carried by the interflow and naturally occurring organics and clay particles that accumulate at the same depths. As result, it was necessary to collect ADCP data and conductivity profiles concurrently to accurately identify the Las Vegas Wash interflow.

Figure 4 contains plots of ADCP signal strength data for a transect across Las Vegas Bay through station LVB4.95 and the temperature and conductivity profiles collected at LVB4.95. The ADCP data showed the Las Vegas Wash interflow was located at between 9 to14 meters deep. The interflow detected with the ADCP agrees very closely with the conductivity plume shown in the profile plot. The Las Vegas Wash interflow was confined within the thermocline and concentrated near the right bank. In addition, the ADCP data showed that the Las Vegas Flood plume was concentrated near the right bank and the vertical extent of the flood plume covered a range from about 20 to 30 meters deep. The conductivity profile showed an elevated conductivity within the flood plume.

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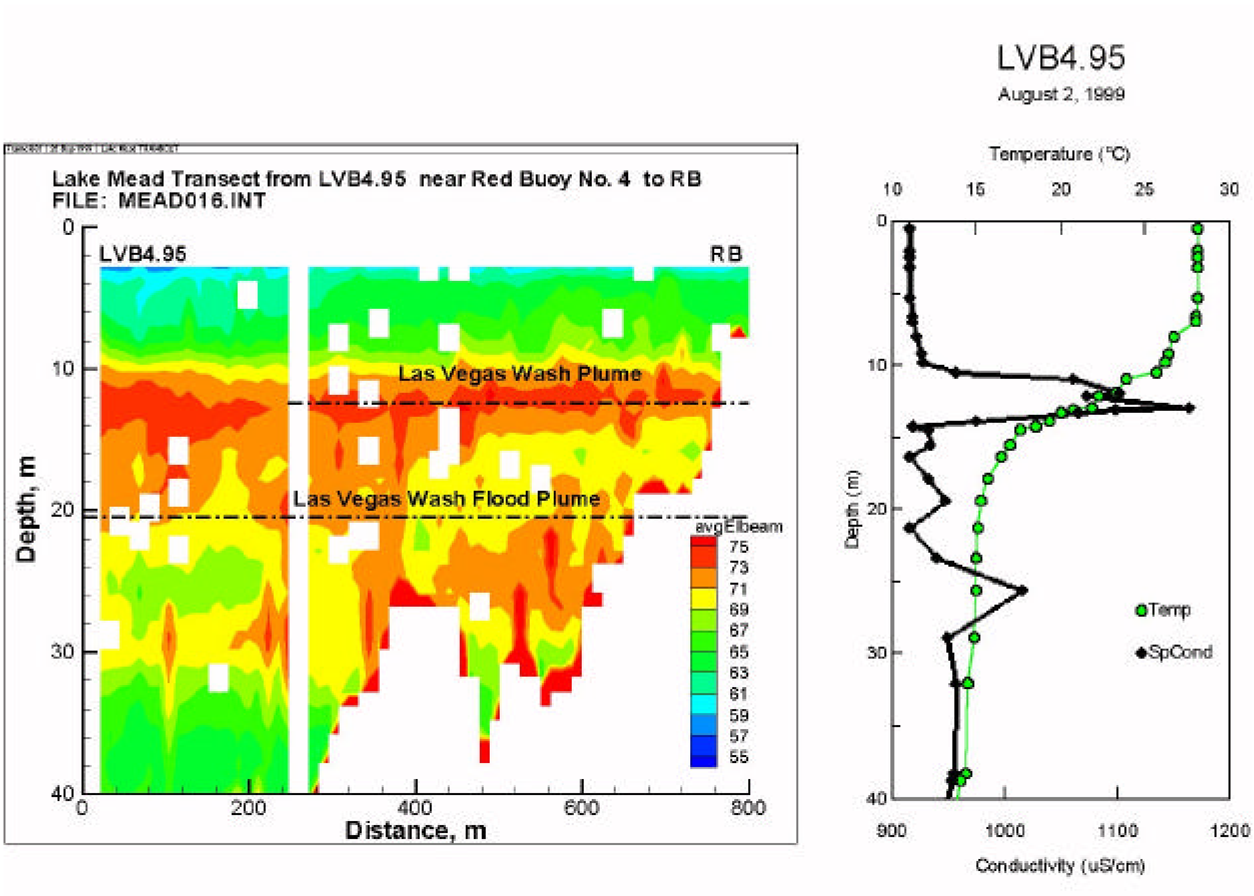

Figure 4. ADCP transect from LVB4.95 to the right bank. The plot on the right shows the temperature and conductivity profiles for station LVB4.95.

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