

# Baroclinic two-layer flow induced by extreme discharge from a dam in a narrow channel



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## ABSTRACT

Long-term current observations were taken in the narrow Noryang Channel during extreme discharge and small discharge periods from a river dam. The Noryang Channel connects the west Gwangyang and east Jinju bays in southern Korea. Jinju Bay is relatively isolated from the open sea by many islands, whereas Gwangyang Bay is connected to the open sea through a wide, deep channel. Jinju Bay is closer to the river dam than Gwangyang Bay. The residual mean flow in the channel over the observation period showed a baroclinic two-layer flow as in an estuary during the large discharge period, whereas barotropic flow was present during the small discharge period. During the large discharge period, the upper layer of water flowed continuously westward, whereas the lower layer flowed eastward. Hydrographic data observed along the channel showed that Gwangyang Bay water was relatively saline and heavier during the large discharge period. This spatial difference in water density might be the result of a large inflow of discharge into Jinju Bay and relatively strong mixing between the water in Gwangyang Bay and the open sea. The salinity in the more isolated Jinju Bay was lower. Simple analytical model calculations showed that horizontal density difference during the large discharge period could drive the surface current flow westward, whereas that of the dense water of the lower layer in Gwangyang Bay flowed eastward through the Noryang Channel.

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## 1. Introduction

Two-layer estuarine circulation is driven by the seaward-directed barotropic pressure gradient and the landward-directed baroclinic pressure gradient (Officer, 1976). In contrast to estuarine circulation, baroclinic two-layer flow in shallow channels connecting bays in coastal regions has not been noted before because the tidal current is relatively strong in such areas. Most research has focused on barotropic flow due to tides in channels between bays (Warner et al., 2002). Two-layer flow in a channel-bay system could be a key process in determining the distribution of water masses and pollutants in neighboring bays, as in strait-basin systems.

As a result of many small islands and complex coastlines, a variety of shoreline types and landforms can be observed along the

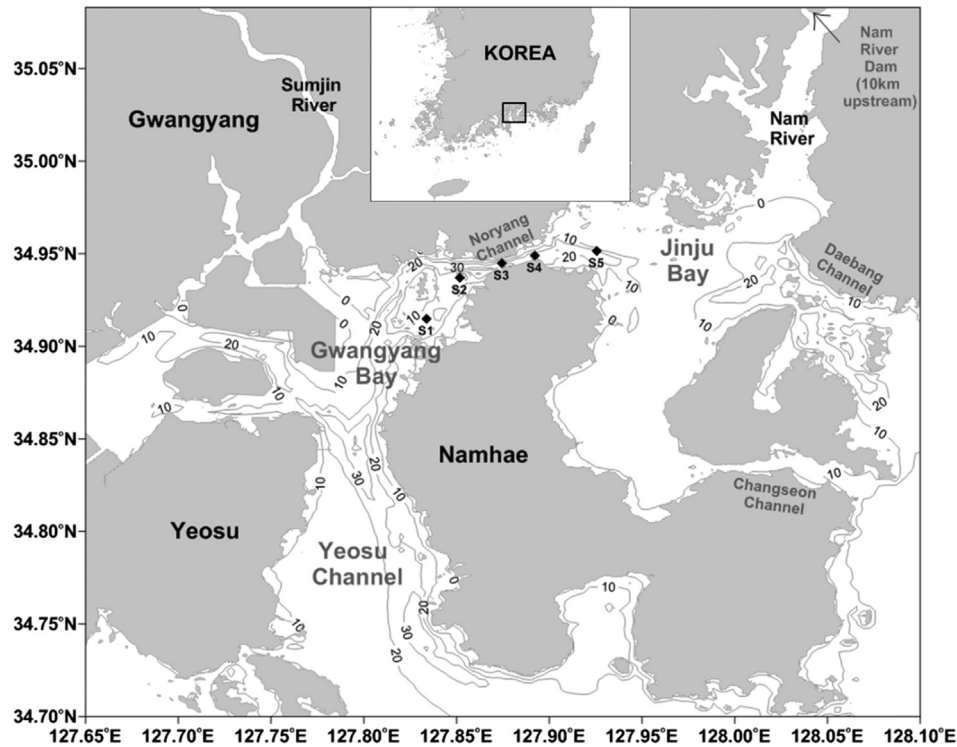
south coast of the Korean Peninsula. Complex coastlines produce many different topographical bay types. Gwangyang Bay and Jinju Bay, which are located on the south coast of Korea, have typically different topographies. The two bays are connected by the narrow Noryang Channel, which has a width of 600 m and a maximum depth of 30 m (Fig. 1). Gwangyang Bay has a wide entrance that connects it to the open sea, whereas Jinju Bay is largely isolated and only connected to the open sea by two channels: the Changseon and Daebang channels. There is little water exchange between Jinju Bay and both channels because the Changseon Channel is shallow and narrow and the Daebang Channel has many small islands that block the flow.

The bay-channel system varies in depth from 5 to 30 m. Most of Jinju Bay is shallow (less than 10 m), whereas Gwangyang Bay is relatively deep (more than 10 m), as shown in Fig. 1. The shallow area that is less than 5 m deep in the southern part of Jinju Bay has been widely developed.

The tides in the study area are predominantly semidiurnal, with mean spring and neap ranges of about 3 m and 1 m, respectively

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**Fig. 1.** Bathymetry of Gwangyang Bay and Jinju Bay, south coast of Korea. Diamonds represent the CTD observation stations. Numbers indicate depths (units: m). The Nam River dam is about 10 km upstream from the Nam River mouth.

(Choo et al., 2002). The tidal current in the Noryang Channel is governed by the tides propagated through Gwangyang Bay, as Jinju Bay is almost blocked by islands. The Tsushima Current in the open sea south of the two bays flows from west to the east all year round (Choo et al., 2009, 2013).

The Sumjin River discharges into Gwangyang Bay, and it had an annual mean discharge of about  $118 \text{ m}^3/\text{s}$  in 2003 and  $109 \text{ m}^3/\text{s}$  in 2012. Moreover, a branch of the Nam River discharges into Jinju Bay, and it had an annual mean discharge of about  $132 \text{ m}^3/\text{s}$  in 2003 and  $92 \text{ m}^3/\text{s}$  in 2012. When there are large amounts of precipitation, the discharge from the branch of the Nam River increases greatly from the Nam River dam; this is done to minimize damage in areas along the Nam River where large populations reside. Such discharges of fresh water mainly occur during the summer monsoon season, and annual mean data show that more than 80% of the river discharge is released during the summer. There was an unprecedented discharge from the Nam River dam due to heavy rain in July 2003.

Recent coastal development activities, such as the construction of an industrial complex and frequent channel dredging that may increase pollutant levels in Gwangyang Bay, invoked a study on circulation patterns to predict water quality changes in this area (Park et al., 2005). Jinju Bay has one of the largest sea farms on the south coast of Korea. Many fisheries are concerned with flow in the Noryang Channel that connects the two bays because the residual current in the channel might deliver pollutants produced in Gwangyang Bay into Jinju Bay. The inflow of polluted water to the sea farm may be critical to fish.

This paper reports on two detailed observations of different flows in the Noryang Channel, which connects the two bays, according to the discharges from the Nam River dam. An analytical model was used to understand dynamically the main cause of the different flows in the channel.

## 2. Observations

Two current observations were undertaken at 7 and 15 m depths at station S3 (see Fig. 1) from 26 June to 24 July 2003 and at whole depths from 4 June to 19 June 2012 in order to understand the current structure in the Noryang Channel. The water depth at the mooring station was 30 m. Compact-electromagnetic (EM) shelf recording current meters (Alec Company, Japan) and a Workhorse sentinel Acoustic Doppler Current Profiler (ADCP) (Teledyne RD Instruments) were used in 2003 and 2012, respectively, to measure the currents. Accuracies of the Compact-EM current meter with respect to speed and direction were  $1 \text{ cm/s}$  and  $2^\circ$ , respectively. Those of the ADCP with respect to speed and direction were  $7 \text{ cm/s}$  and  $2^\circ$ , respectively.

Conductivity–temperature–depth (CTD) observations were performed at five stations (Fig. 1) on 13 July 2003 and 19 June 2012. A Sea Bird Electronics SBE 19 and IDRONAUT Ocean Seven 304 CTD with temperature accuracies of  $0.01^\circ\text{C}$  and  $0.005^\circ\text{C}$ , respectively, and conductivity accuracies of  $0.001 \text{ s/m}$  and  $0.007 \text{ s/m}$ , respectively, were used for the CTD observations. Hydrographic data were collected from the surface to the bottom of the channel at 1 m intervals.

The wind speeds and directions during the current observation periods were compared. The data were provided by the Korea Meteorological Administration. Overall, for both periods, the mean wind speeds were low and the wind directions were almost same. The mean wind speed and direction were  $0.63 \text{ m/s}$  and  $140.5^\circ$  in July 2003 and were  $0.27 \text{ m/s}$  and  $143.1^\circ$  in June 2012.

## 3. Results

### 3.1. Hydrography

To investigate the effect of extreme river discharge from a dam on the circulation in the channel, vertical sections of the

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