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Climatic, coastal and anthropogenic forcing of geomorphic hazards in a high-relief patagonian coastal city: Comodoro Rivadavia, Argentina.

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ABSTRACT

Comodoro Rivadavia, on the Patagonian Atlantic coast of Argentina, is a high-relief city where semiarid climate, steep ephemeral catchments, weak Cenozoic sedimentary successions and macrotidal coastal dynamics interact with urban and industrial land use. This study provides an integrated assessment of flood, landslides, coastal erosion, port sedimentation and urban-connectivity disruption based on previous studies, updated meteorological records, geomorphic mapping, field observations, drone-derived topography, multitemporal coastal imagery and bathymetric data. The 1956-2022 rainfall record confirms the exceptional magnitude of the March-April 2017 storm, with 399.4 mm of accumulated rainfall and 232 mm in one day, while a 2022 extreme event indicates persistent exposure to high-magnitude storms. Flood impacts include gully erosion, channel widening, drainage obstruction, urban sedimentation and coastal sediment delivery; however, mitigation remains incomplete because one of four planned check dams is operative in the De La Quinta catchment. Slope stability is controlled by lithological contrasts, groundwater or marine triggers and anthropogenic modification, including drainage alteration, irrigation, slope-foot excavation and occupation of relict landslide deposits. The 2023 Cerro Chenque landslide reactivation, triggered by storm surges that intensified toe erosion, involved approximately 70,425 m^3 and closed National Route 3 for 35 days. Between Punta Borja and Playa de Tanques YPF, cliff retreat reaches 0.67 to 1.18 m yr^{-1}, whereas more than 250,000 m^3 of sediment accumulated in the port between 1996 and 2022. The results show that risk reduction requires process-based, multi-hazard territorial planning rather than isolated engineering responses.

Keywords: Extreme rainfall events, coastal hazard and interventions, storm surge, shallow landslides, urban land use.

RESUMEN

Forzantes climáticos, costeros y antropogénicos de los peligros geomorfológicos en una ciudad costera patagónica de alto relieve: Comodoro Rivadavia, Argentina. Comodoro Rivadavia, en la costa atlántica patagónica de Argentina, es una ciudad de alto relieve donde el clima semiárido, las cuencas efímeras de fuerte pendiente, las sucesiones sedimentarias cenozoicas poco competentes y la dinámica costera macromareal interactúan con el uso urbano e industrial del suelo. Este estudio integra antecedentes, registros meteorológicos, mapeo geomorfológico, observaciones de campo, topografía derivada de drones, imágenes multitemporales y datos batimétricos para evaluar inundaciones, deslizamientos, erosión costera, sedimentación portuaria y disrupción de la conectividad urbana. El registro de 19562022 confirma el carácter excepcional de la tormenta de marzoabril de 2017, con 399,4 mm acumulados y 232 mm en un día; un evento de 82 mm/día en 2022 demuestra la persistencia de tormentas de alta magnitud. Las inundaciones generan erosión por cárcavas, ensanchamiento de canales, obstrucción del drenaje, sedimentación urbana y aporte sedimentario a la costa, mientras que la mitigación sigue siendo incompleta, con solo uno de cuatro diques de retención operativo. La inestabilidad de laderas responde a contrastes litológicos, disparadores subterráneos o marinos y modificaciones antrópicas. En 2023, la reactivación del deslizamiento del Cerro Chenque, favorecida por marejadas y erosión basal, movilizó aproximadamente 70.425 m^3 y cerró la Ruta Nacional 3 durante 35 días. Entre Punta Borja y Playa de Tanques YPF, el retroceso de acantilados alcanza 0,671,18 m año^{-1}, y más de 250.000 m^3 de sedimentos se acumularon en el puerto entre 1996 y 2022. La reducción del riesgo requiere una planificación territorial multipe.

Palabras clave: Eventos extremos de precipitaciones, riesgos costeros e intervenciones, mareas de tormenta, deslizamientos someros, uso del suelo urbano.

INTRODUCTION

Coastal cities located in high-relief settings are increasingly exposed to the combined effects of extreme rainfall, slope instability, storm surges, sea-level rise, and accelerated land-use change. In these environments, geomorphic hazards do not operate as isolated processes: short-duration rainfall events may trigger flash floods in steep catchments, increase sediment supply from hillslopes and urban surfaces, promote shallow landsliding, and deliver large sediment volumes to coastal systems. At the same time, marine forcing may enhance cliff retreat, destabilize coastal slopes, and reduce the effectiveness of rigid engineering structures. These process interactions are particularly relevant under current and projected climate-change scenarios, in which rainfall extremes, coastal erosion and flood exposure are expected to increase in many urbanized coastal regions (Nicholls et al. 2007, Gariano and Guzzetti 2016, Alfieri et al. 2017, Wright and Thom 2023).

Although floods, landslides and coastal erosion have been widely studied as individual hazards, fewer studies have examined how they interact in urban areas where natural geomorphic susceptibility is amplified by anthropogenic modifications. In high-relief coastal cities, urbanization may increase impervious surfaces, alter runoff pathways, concentrate drainage discharge, load unstable slopes, promote excavation at slope toes, increase artificial water input through irrigation or leaking infrastructure, and modify sediment budgets through coastal defenses and port structures. Therefore, the assessment of urban risk requires moving beyond single-process descriptions toward an integrated geomorphological framework that considers feedbacks among climatic forcing, inherited landforms, sedimentary substrates, and human interventions (Gill and Malamud 2017, Capandeguy and Sprechmann 2021).

Comodoro Rivadavia, located on the Atlantic coast of central Patagonia along the San Jorge Gulf, provides a representative case of a high-relief coastal city affected by interacting hydrogeomorphic, mass-movement and coastal processes. The city is emplaced within a semiarid climatic setting, crossed by seven ephemeral drainage catchments with steep longitudinal gradients, and bounded by coastal cliffs developed on weakly to moderately consolidated Cenozoic sedimentary successions (Paredes et al. 2020, 2021). Alternations of claystones, tuffaceous deposits, sandstones and conglomerates favor differential erosion, groundwater-controlled instability and landslide development, whereas the macrotidal coast is affected by storm waves, cliff retreat and localized sediment accumulation. These inherited geomorphological and geological conditions coexist with rapid urban expansion, industrial infrastructure, hydrocarbon-related land disturbance and occupation of low-lying outlets, steep slopes and coastal margins (Sciutto et al. 2008, Codignotto 2021).

Previous studies have documented several components of this environmental problem in Comodoro Rivadavia, including geological hazards on unstable slopes (Hirtz et al. 1994, Hirtz and Blachakis 2000, González et al. 2002), the 1995 Cerro Chenque landslide (Hirtz et al. 2019), coastal erosion between Punta Alta and Punta Borja (Gómez et al. 2003), macrotidal beach dynamics in the San Jorge Gulf (Codignotto and Del Valle 1995, Kokot et al. 1996; Isla et al. 2002), and the geomorphological and sedimentological impacts of recent extreme rainfall events (Paredes et al. 2017, 2020). However, these contributions have generally emphasized specific hazards, sectors or events. A remaining gap is the lack of an integrated assessment that explicitly links ephemeral-catchment flooding, rainfall- and wave-triggered slope instability, coastal erosion and sedimentation, and anthropogenic modification of terrain within a common multi-hazard framework relevant to urban development.

In this contribution, Comodoro Rivadavia is interpreted as an urban geomorphic system in which hazard conditions emerge from the coupling among three groups of controls. The first group includes climatic and oceanographic forcing, such as high-intensity rainfall, dry antecedent conditions, wind regime, tides and storm waves. The second group includes inherited susceptibility factors, such as relief amplitude, catchment morphology, lithological contrasts, expansive clay-rich intervals, structural discontinuities, coastal cliffs and macrotidal shoreface dynamics. The third group includes anthropogenic drivers, including urban expansion over unstable or flood-prone terrain, increased impervious cover, artificial drainage concentration, slope excavation, irrigation and water leakage on low-permeability substrates, hydrocarbon-related surface disturbance, coastal armoring, port infrastructure and incomplete flood-mitigation works. The interaction among these controls may produce nonlinear responses, whereby low-frequency, high-magnitude events generate disproportionate geomorphic and infrastructural impacts (Schumm 1973, Pacheco Quevedo et al. 2023).

This paper provides an integrated geomorphological assessment of floods, landslides, coastal erosion and coastal sedimentation in Comodoro Rivadavia, based on a critical synthesis of previous studies and the analysis of geomorphic, topographic, bathymetric, meteorological and field-based evidence. Rather than attributing individual events solely to climate change or to urbanization development, the study aims to distinguish inherited geomorphic susceptibility from recent climatic and anthropogenic drivers, identify the main process interactions affecting urban infrastructure and connectivity, and develop a conceptual framework for multi-hazard territorial planning in high-relief coastal cities of semiarid Patagonia.

STUDY AREA

Location and physiographic setting

Comodoro Rivadavia is located in southeastern Chubut Province, central Patagonia, on the Atlantic coast of the San Jorge Gulf, Argentina (Fig. 1A). The city has an urban area of approximately 558.2 km² and a population close to 250,000 inhabitants, with residential, industrial, port, road and hydrocarbon-related infrastructure distributed across a rugged coastal landscape. The urban area is crossed by seven ephemeral drainage systems that flow eastward into the Atlantic Ocean: La Mata stream, De La Quinta stream, Km 3 basin, Belgrano stream, Restinga Alí stream, Caleta Córdova basin and Cañadón Biggs basin (Fig. 1B). These catchments have no perennial rivers and are activated mainly during rainfall events.

The drainage network extends from sea level at the coastal outlets to 751 m a.s.l. along the drainage divide located on the Pampa del Castillo and Pampa de Salamanca surfaces. The combined catchment area is approximately 1546 km², and the longest stream courses show longitudinal gradients between 0.0027 and 0.0371 m/m. This relief configuration favors rapid runoff concentration during high-intensity rainfall events, particularly where ephemeral channels enter low-lying urban sectors near the basin outlets (Paredes et al. 2021).

Geological and geomorphological controls

The regional landscape of extra-Andean Patagonia is characterized by extensive elevated, low gradient, gravel-covered surfaces locally known as “pampas”, which reach elevations of up to 750 m a.s.l. and are commonly interpreted as remnants of late Cenozoic fluvial systems associated with glacial-meltwater episodes and subsequent relief inversion (Césari and Simeoni 1994, Simeoni 2008, Martínez and Kutschker 2011). East of these elevated surfaces, the study area is dominated by dissected structural relief drained by short, steep, ephemeral catchments that debouch directly into the Atlantic coast (Fig. 1B–C).

The erosional landscape around Comodoro Rivadavia is developed on Cenozoic sedimentary units of the Golfo San Jorge Basin. The lower exposed intervals include tuffaceous deposits of the Sarmiento Formation, overlain by marine deposits of the early-middle Miocene Chenque Formation and continental deposits of the middle Miocene Santa Cruz Formation (Foix et al. 2025). From a geomorphological perspective, the most relevant feature of this succession is the alternation of relatively resistant sandstones and conglomerates with weak, clay-rich and tuffaceous intervals. This lithological contrast promotes differential erosion, seepage along permeable sandstone beds, undercutting weak intervals, block falls and slope instability.

Ephemeral channels are commonly inactive under normal hydrological conditions, but during storms they may rapidly convey water and sediments through low-sinuosity or braided reaches. Localized incised meanders may occur near basin outlets, whereas gullies are frequent on steep slopes and poorly consolidated deposits during intense runoff events (Paredes et al. 2020). Slope instability is favored by relief amplitude, steep valley flanks, lithological contrasts, structural discontinuities and the presence of weak clay-rich levels. Rotational and translational landslides have been documented both within the urban area (Hirtz et al. 1994, Hirtz and Blachakis 2000, Hirtz et al. 2019) and in the high-relief

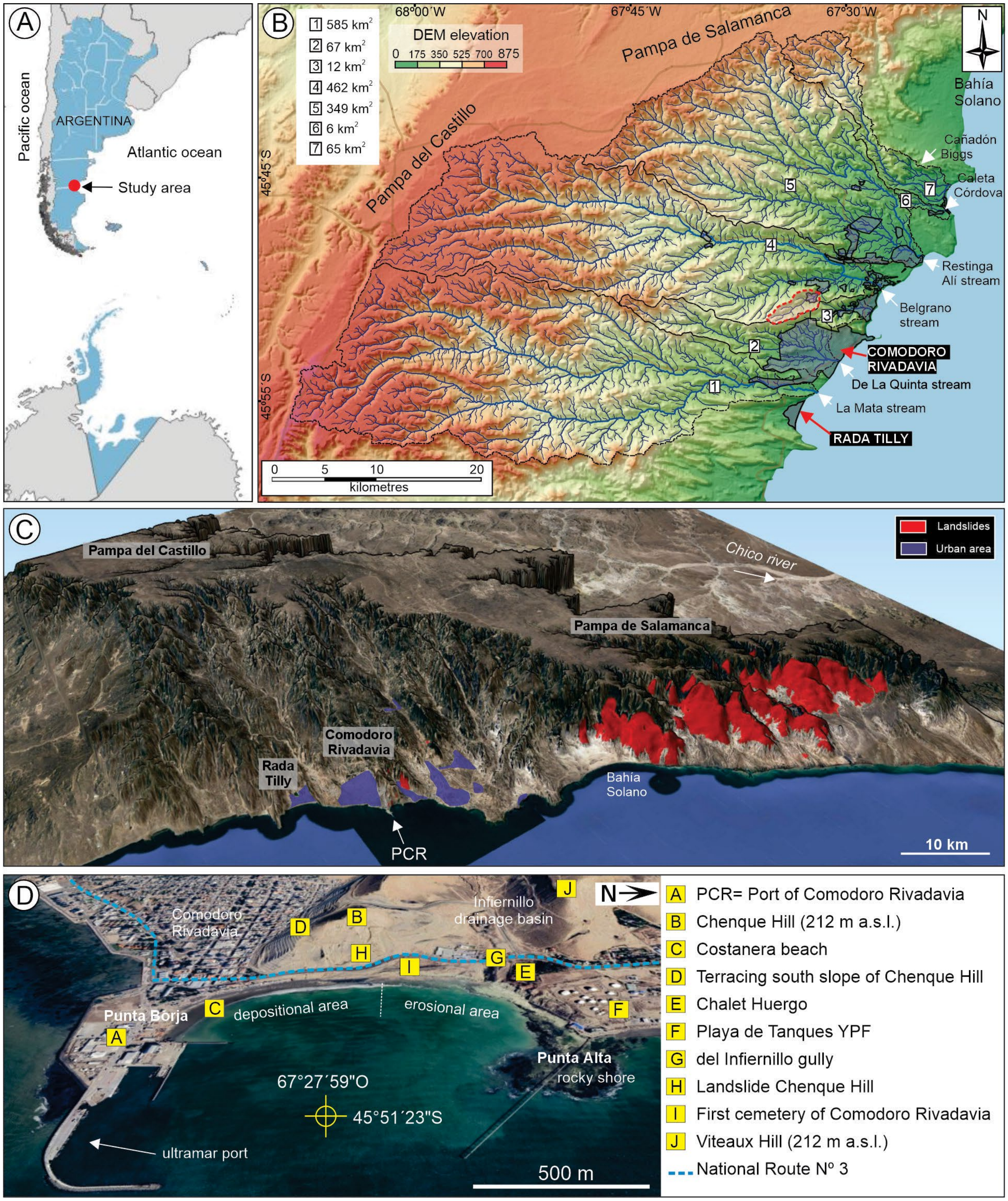

Figure 1. Location maps. (A) General location of the study area in Argentina. (B) Catchment areas and main tributaries of seven ephemeral fluvial systems surrounding Comodoro Rivadavia and Rada Tilly cities. Comodoro Rivadavia's neighborhoods are shown in pale violet. Key: 1. La Mata stream, 2. De La Quinta stream, 3. Km 3 basin, 4. Belgrano stream, 5. Restinga Alí stream, 6. Caleta Córdova basin, 7. Cañadón Biggs basin. The inset displays catchment areas. The Laprida subbasin within the Arroyo Belgrano basin is marked by a red dotted line. Based on SRTM Digital Elevation Model SRTM1S46W068V3. (C) Oblique satellite image of the study area, highlighting the elevated slope of the drainage catchments, and the occurrence of large-scale landslides northward of Bahía Solano (in red). Vertical exaggeration is 6:1. PCR is the Port of Comodoro Rivadavia. (D) Satellite image and main features of the coastal area located immediately north of PCR. The geomorphic and anthropogenic elements of interest for this study are indicated with capital letters. Satellite images courtesy of Google Earth™.

coastal escarpments north of Bahía Solano (González Díaz 2004, Kilnar et al. 2024, Pánek et al. 2025a, b). Within the city, Cerro Chenque, a 212 m high coastal hill adjacent to National Route 3 and the downtown area, represents the most critical geomorphic feature because of its history of rockfalls, slope deformation and large landslide activity.

Urban land use and anthropogenic setting

Urban development in Comodoro Rivadavia occupies several geomorphologically sensitive settings: low-lying areas near ephemeral-stream outlets, steep slopes within drainage catchments, coastal sectors affected by cliff retreat, and areas located downslope from landslide-prone landmasses (Fig. 1B–D). These sectors concentrate housing, roads, public spaces, industrial facilities and strategic infrastructure, including the Port of Comodoro Rivadavia (hereafter PCR) and National Route 3. The spatial overlap between urban growth and unstable landforms is a central factor controlling present-day exposure to flooding, landslides and coastal erosion.

Anthropogenic modifications affect the geomorphic response of the study area at different scales. Within the urbanized catchments, impervious surfaces, road embankments, channel rectification, stormwater drainage works, aggregate extraction, waste accumulation and surface disturbance modify runoff pathways and sediment availability. On slopes, excavations at the toe, road cuts, building loads, deficient drainage, artificial irrigation of public spaces and leakage from water or sewer infrastructure may increase pore-water pressure or reduce slope stability in unconsolidated substrates. In the upper and middle parts of the drainage basins, hydrocarbon development is also extensive, with more than 7,000 oil well sites and associated infrastructure west of the city. These interventions contribute to vegetation removal, surface compaction, drainage disruption and enhanced sediment supply during storms (Paredes et al. 2021).

The coastal sector between the PCR and Chalet Huergo combines natural and artificial controls. Previous studies recognized wave-energy concentration near Punta Alta, erosion along coastal cliffs, and sediment accumulation in the bay adjacent to the PCR and the Costanera sector after the construction of port and coastal protection structures (Kokot et al. 1996, Gómez et al. 2003). Therefore, the current coastal morphology reflects the interaction between macrotidal processes, storm waves, cliff erosion, littoral drift, sediment supply from ephemeral catchments and anthropogenic modification by breakwaters, revetments and port infrastructure.

Climate and coastal forcing

Comodoro Rivadavia has a temperate semiarid climate, classified as BWk according to the Köppen–Geiger system (Coronato et al. 2017, Beck et al. 2023). Meteorological records from the General Enrique Mosconi Airport station indicate a mean annual temperature of 13.5 °C for the 1956–2022 period, with mean monthly values ranging from 6.6 °C in July to 19.4 °C in January. During this timeframe, the average annual temperature has shown a gradual increase of 0.7°C (Fig. 2A). Mean annual precipitation is 244.4 mm, concentrated mainly between April and July, whereas potential evapotranspiration reaches approximately 704 mm/year, resulting in a marked annual water deficit (Hernández et al. 2017).

Rainfall distribution is highly irregular. Daily precipitation events exceeding 15 mm/day correspond to the upper 5% of the 1956–2022 record, whereas events exceeding 35 mm/day and 63 mm/day represent the upper 1% and 0.1%, respectively (Fig. 2B). Annual and monthly averages therefore provide only a partial representation of the local hydroclimatic regime, because a large proportion of annual rainfall may occur during a few days. This behavior is critical for ephemeral catchments, where high-intensity storms can rapidly generate surface runoff, channel incision, gully erosion and sediment delivery to low-lying urban sectors and the coastal region (Paredes et al. 2020, 2021).

The region is influenced by the Southern Hemisphere Westerlies, with dominant winds from the west and secondary components from the northwest, southwest, south and northeast (Prohaska 1976, Montes et al. 2017). Although westerly winds dominate the annual wind regime, easterly and northeasterly components are relevant because they are associated with Atlantic Ocean moisture transport and coastal storm conditions (Agosta et al. 2019). Data from the weather station at PCR show a predominance of westerly winds during 2019, with secondary modes from WSW, WNW, and NW directions. In contrast, during 2020, the dominant wind direction was from the WSW, with secondary modes from the W and SW. Notably, in both years, a recurrent wind mode from the NE is evident. In 2022, a predominance of winds from the WNW is observed, along with secondary modes of comparable frequency and intensity from the ENE, S, and NW directions (Fig. 2C). The coastline of Comodoro Rivadavia is macrotidal, with tidal ranges greater than 4 m, and is exposed to storm waves and surge events capable of enhancing toe erosion at coastal cliffs. These atmospheric and oceanographic forcings provide the main triggers for the floods, landslides and coastal-erosion processes analyzed in the following sections.

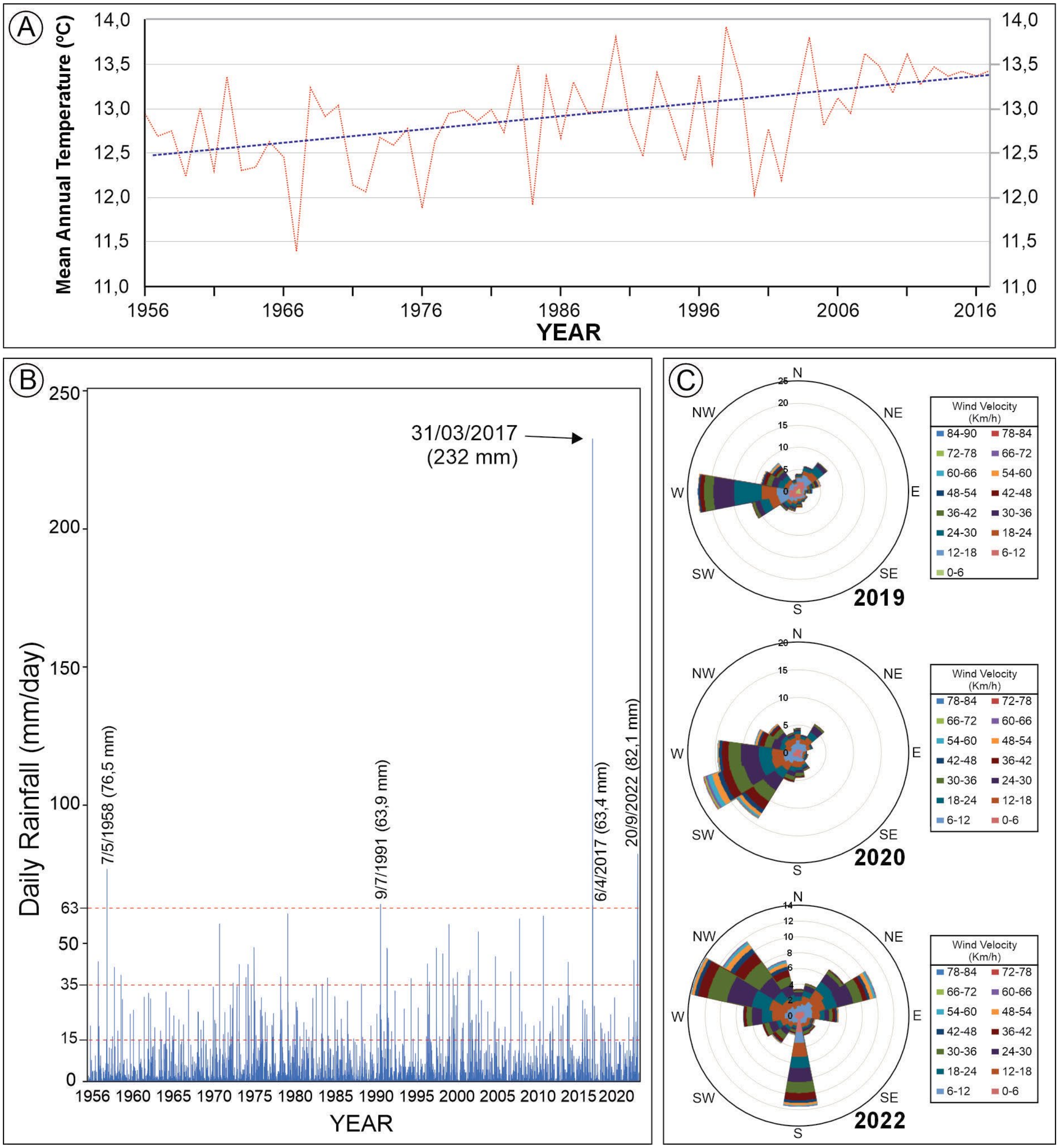

Figure 2. Meteorological data from Comodoro Rivadavia. (A) Mean temperature variations since 1956 and (B) daily rainfall record for 1956–2022, based on Enrique Mosconi Airport data. (C) Wind rose diagrams for 2019, 2020, and 2022 from the Port of Comodoro Rivadavia weather station.

MATERIALS AND METHODS

Research design and data sources

This contribution is an integrated geomorphological assessment of flood hazards, landslide activity, coastal erosion and coastal sedimentation in Comodoro Rivadavia. The study combines: (i) a critical compilation of published and technical background information, (ii) geomorphological mapping based on remote sensing and digital elevation models, (iii) analysis of meteorological and wind records, (iv) comparison of historical aerial photographs, satellite images and drone-derived products, (v) analysis of historical bathymetric surveys in the Port of Comodoro Rivadavia, and (vi) field-based observations of geomorphic processes and anthropogenic modifications.

To avoid mixing previous results with new evidence, the database was organized into three categories. The first category includes published and technical studies used as background information, particularly previous analyses of flash floods, landslides, coastal dynamics and geological hazards in Comodoro Rivadavia and adjacent coastal sectors (Hirtz and Blachakis 2000, 2004, Kokot 2004, González et al. 2002, Gómez et al. 2003, Francisca et al. 2017, Hirtz et al. 2019, Paredes et al. 2017, 2020, 2021). The second category includes spatial datasets processed in this study, such as SRTM digital elevation data, Google Earth™ imagery, historical aerial photographs, drone-derived orthomosaics and bathymetric records. The third category includes original field observations and geomorphic interpretations made by the authors during surveys conducted between 2023-2024.

The methodological workflow was designed to distinguish inherited geomorphic susceptibility from event-related triggers and anthropogenic drivers. For each analyzed process, the following information was compiled: location, geomorphic setting, lithological and topographic controls, triggering factors, anthropogenic modification, type of evidence, and impact on urban infrastructure. This classification was used to build a multi-hazard conceptual framework linking climatic, oceanographic, geological and anthropogenic controls.

Digital elevation analysis and catchment morphometry

The topographic framework of the study area was analyzed using the SRTM Digital Elevation Model SRTM1S46W068V3, complemented by satellite imagery and field observations. The DEM was projected to POSGAR GK F2, coordinates were maintained in latitude/longitude (WGS84), and were processed in QGIS 3.28 to derive elevation, slope, shaded-relief maps, drainage divides and longitudinal stream profiles.

Seven ephemeral drainage catchments crossing the urban area were delimited: La Mata stream, De La Quinta stream, Km 3 basin, Belgrano stream, Restinga Alí stream, Caleta Córdova basin and Cañadón Biggs basin. Catchment areas, elevation ranges and longitudinal gradients of the main channels were calculated from the DEM. These morphometric parameters were used to characterize the potential for rapid runoff concentration during high-intensity rainfall events and to support the spatial interpretation of flood-prone urban sectors.

Geomorphic units were mapped by visual interpretation of DEM-derived shaded relief, Google Earth™ imagery and available orthomosaics. The mapped features include ephemeral channels, gully systems, low-lying depositional areas, steep slopes, landslide scars, landslide deposits, coastal cliffs, abrasion platforms, beach and berm deposits, artificial fills, port structures and coastal defenses. Previously mapped features from published studies were included only when their source was explicitly cited; features mapped or reinterpreted in this contribution are indicated as original interpretations.

Hydroclimatic and wind data analysis

Meteorological data from the General Enrique Mosconi Airport station were used to characterize temperature and rainfall variability in Comodoro Rivadavia for the 1956–2022 period. The dataset includes mean annual temperature, annual precipitation and daily precipitation records. Daily rainfall events were classified using percentile thresholds calculated from the complete daily record: intense events correspond to the upper 5% of daily rainfall values, very intense events to the upper 1%, and extreme events to the upper 0.1%. These thresholds correspond, respectively, to values greater than 15 mm/day, 35 mm/day and 63 mm/day in the analyzed record.

To address whether rainfall intensity shows temporal changes or whether recent events are isolated, the annual number of intense, very intense and extreme daily rainfall events was calculated for the 1956–2022 period. In addition, the annual maximum daily precipitation series was analyzed to identify the occurrence and recurrence of high-magnitude rainfall events. Temporal trends were evaluated using ordinary least-squares regression.

Wind data were obtained from the meteorological station located at the Port of Comodoro Rivadavia for the years 2019, 2020 and 2022. Wind direction and velocity were processed to produce wind-rose diagrams and to characterize dominant and secondary wind modes. Attention was paid to easterly and northeasterly wind components because of their potential association with Atlantic Ocean moisture transport, storm-wave conditions and coastal erosion episodes.

Landslide and slope-instability analysis

Landslide-prone areas were identified by combining previous geological-hazard studies, visual interpretation of aerial and satellite images, field observations and topographic analysis. Attention was paid to sectors where urban infrastructure is located on or below unstable slopes, including Barrio Sismográfica, the flanks of Cerro Chenque, coastal cliffs near Playa de Tanques YPF and Chalet Huergo, and steep slopes within the Km 3 and Km 4 drainage basins.

For the Cerro Chenque sector, topographic changes associated with the August 30th 2023 landslide were analyzed through aerial photogrammetry obtained on June 22, August 23, August 29, September 3, and September 29, using a Drone DJI Matrice 300 RTK with a CHCNAV Alpha Air 450 LIDAR sensor, and a receiver GNSS RTK CHC i73, which provided a vertical resolution of 3 cm and a pixel size of 1.5

cm. The field surveys were done with SouthField software and the office processing with SGO (South Geomatics Office). Elevation differences were calculated by subtracting pre-event and post-event surfaces within a manually mapped landslide polygon. Areas of negative and positive elevation change were interpreted as depletion and accumulation zones, respectively. The displaced volume was estimated by integrating elevation differences over the affected area, after removing noise below the vertical error threshold of the photogrammetric model.

Slope-instability indicators were mapped from field and image-based evidence, including scarps, cracks, displaced blocks, rockfalls, toe erosion, seepage zones, irrigated surfaces, road cuts, slope-foot excavations and drainage outlets. Anthropogenic pressures were assessed semi-quantitatively by recording the presence or absence of building loads, artificial irrigation, water-distribution or sewer infrastructure, road cuts, surface drainage concentration, coastal defenses and hydrocarbon-related disturbance. Because no systematic subsurface geotechnical dataset is available for all slopes, the study does not calculate factor-of-safety values; instead, it evaluates spatial coincidence and process plausibility between anthropogenic modifications, susceptible lithologies and observed slope deformation.

Coastal change analysis

Coastal geomorphic changes were analyzed in the sector between the Port of Comodoro Rivadavia, the Costanera area, Cerro Chenque, Playa de Tanques YPF and Chalet Huergo. This sector was selected because it contains both erosional and depositional coastal compartments, urban infrastructure, coastal defenses and recent slope failures.

Historical shoreline and cliff-position changes were assessed by comparing a 1968 aerial photograph with a 2023 drone-derived orthomosaic. The aerial photograph was georeferenced using stable control points identifiable in both datasets, such as road intersections, rocky outcrops and persistent urban features. The 1968 cliff line, shoreline and railway-track position were digitized and compared with the 2023 cliff position. Cliff retreat distances were measured along transects oriented approximately perpendicular to the local cliff trend. Mean retreat rates were calculated by dividing the measured retreat distance by the time interval between both datasets. Uncertainty was estimated from georeferencing residuals, image resolution and digitizing errors.

Current coastal landforms were mapped from the 2023 orthomosaic and field observations. The mapped features include active cliffs, abrasion platforms, block-fall deposits, beach deposits, berms, rocky revetments, seawalls, breakwaters, erosion scarps and areas of sediment accumulation. These features were used to distinguish sectors dominated by cliff erosion from sectors dominated by sediment accumulation and port infill.

Bathymetric and port-infill analysis

Bathymetric changes in the Port of Comodoro Rivadavia (PCR) were analyzed using historical bathymetric surveys conducted between 1996 and 2022 by the Administración Portuaria del Puerto de Comodoro Rivadavia. All bathymetric datasets were checked for coordinate system, vertical datum and spatial coverage before comparison. Where necessary, datasets were transformed to a common horizontal projection and vertical reference level.

Bathymetric points and contour data were interpolated to generate gridded bathymetric surfaces using kriging. The same grid resolution was used for all surveyed years to ensure comparability. Bathymetric difference maps were generated by subtracting older surfaces from younger surfaces, allowing identification of erosion and aggradation areas. Vertical accretion rates were calculated by dividing elevation change by the time interval between surveys.

Sediment-volume changes were calculated within a fixed polygon corresponding to Area A of the port sector, defined in Fig. 9A. The volume of accumulated sediment was obtained by integrating positive elevation differences within this polygon. Cross-sections were extracted along two fixed transects to evaluate the geometry of the infill body and the temporal evolution of the harbor floor. The results were used to identify phases of port infill and to evaluate whether sediment accumulation was continuous or concentrated after high-magnitude rainfall and coastal-storm events.

Assessment of anthropogenic controls and urban exposure

Anthropogenic controls were evaluated by mapping the spatial relationship between geomorphic hazards and urban or industrial infrastructure. Urbanized areas, roads, stormwater drainage works, port structures, coastal defenses, check dams, hydrocarbon facilities, road cuts, slope excavations, public irrigated areas and areas of informal or dense occupation were mapped using satellite imagery, field observations and available published information.

For flood-prone catchments, the analysis considered the position of urban areas relative to channel outlets, low-gradient depositional zones and projected or constructed flood-mitigation structures. The De La Quinta catchment was examined in more detail because it includes planned check dams R1, R2, R4 and R7, of which only R4 is currently operative. The analysis compared the intended spatial distribution of the mitigation system with the present state of construction to assess residual exposure of downstream urban areas.

For slope instability, anthropogenic controls were analyzed in relation to susceptible lithologies and geomorphic position. The analysis considered whether observed instabilities were associated with slope-foot excavation, building load, artificial irrigation, deficient drainage, leaking infrastructure, vegetation removal, road construction or marine undercutting. For the coastal sector, the analysis considered how breakwaters, seawalls and rocky revetments modify wave reflection, sediment trapping, downdrift erosion and cliff-toe protection.

GEOMORPHIC IMPACTS OF CLIMATE, COASTAL AND ANTHROPOGENIC FORCING

Extreme rainfall events, urban floods and incomplete mitigation infrastructure

Rainfall thresholds and recent high-magnitude events. Daily precipitation records for the 1956–2022 period show that rainfall in Comodoro Rivadavia is highly irregular and strongly event-controlled (Fig. 2B). The mean annual precipitation is 244.4 mm, but this average does not adequately represent the hydrological behavior of the region because a substantial proportion of the annual rainfall may occur during a few days.

The updated 1956–2022 daily rainfall series confirms that the March–April 2017 storm was the largest hydrometeorological event recorded in Comodoro Rivadavia since the beginning of instrumental records. During this event, total accumulated rainfall reached 399.4 mm between March 29 and April 8, 2017, equivalent to approximately 163% of the mean annual precipitation. The maximum daily value was recorded on March 31, 2017, with 232 mm/day, exceeding by more than three times the threshold used here to define extreme rainfall events. A second extreme daily value was recorded during the same storm sequence on April 6, 2017, with 63.4 mm/day.

Daily rainfall events exceeding 35 mm have occurred 43 times since 1957. The years 2017 and 2022 are the only ones with three daily events above this threshold (Fig. 3). In 2017, these events accumulated 350 mm, representing 62.4% of the annual precipitation, whereas in 2022 they accumulated 180.9 mm, equivalent to 46.2% of the annual total. These data confirm the exceptional character of the 2017 storm but also indicate that high-magnitude rainfall occurred on September 20, 2022, with 82.1 mm/day. Although the March 31, 2017 rainfall event remains an outlier within the instrumental record, the occurrence of subsequent high-magnitude rainfall events demonstrates that the urban drainage and flood-mitigation system continues to face recurrent exposure to extreme precipitation, highlighting the need for long-term adaptation rather than responses focused on a single catastrophic event. The updated rainfall record therefore supports two complementary results. First, the 2017 event represents

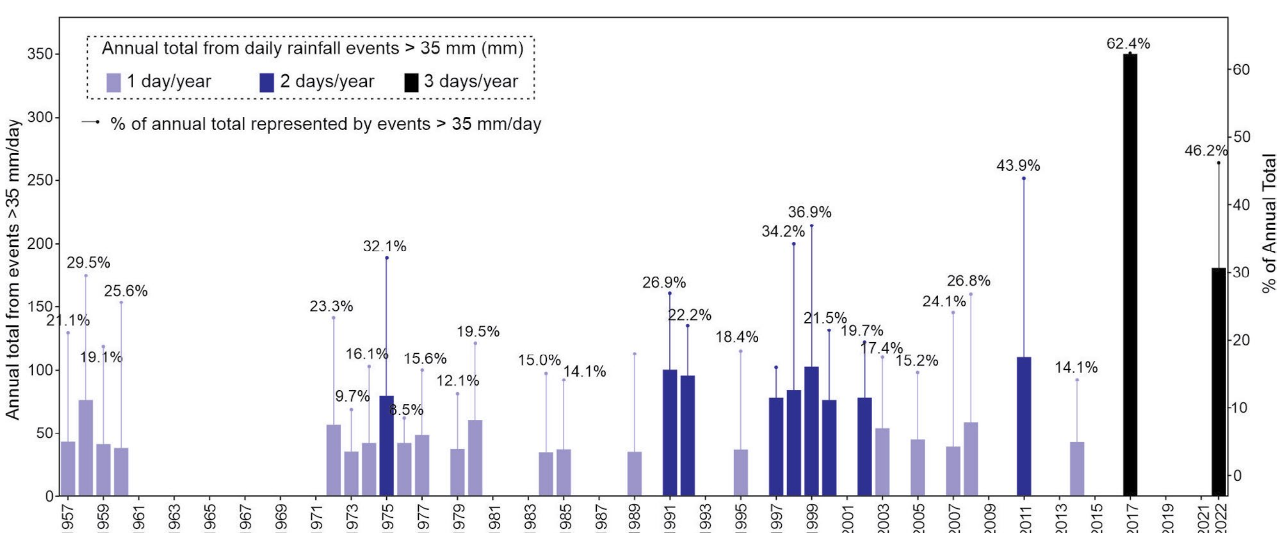

Figure 3. Daily rainfall events ≥35 mm recorded in Comodoro Rivadavia during the 1957–2022 period. Bars show the annual accumulated rainfall (mm) associated with daily events equal to or greater than 35 mm, whereas the line indicates the percentage of the annual rainfall total represented by those events. The color of the bars indicates the number of events recorded each year (1= pink, 2= blue, 3= black). The figure highlights the strong interannual variability in the occurrence and magnitude of high-intensity rainfall events, as well as their contribution to annual precipitation totals, particularly in 2017 and 2022.

an exceptional hydrological forcing in terms of daily rainfall and total storm accumulation. Second, the occurrence of very intense and extreme rainfall after 2017 indicates that the geomorphic and infrastructural vulnerabilities, and preconditioning factors documented for the city should not be interpreted only as the consequence of a single historical event, but as part of a recurrent exposure to low-frequency, high-magnitude rainfall episodes.

Flood pathways, sediment production and urban deposition during the 2017 event. The geomorphological and sedimentological impacts of the March–April 2017 flood were previously analyzed in detail by Paredes et al. (2020, 2021). In this contribution, those published results are used as a baseline for integrating flood impacts with landslide activity, coastal sedimentation and urban infrastructure exposure.

The 2017 storm activated the seven ephemeral drainage systems that cross the urban area of Comodoro Rivadavia and discharge into the Atlantic Ocean. Intense rainfall exceeded the infiltration capacity of dry soils during the initial stages of the event, producing deep gullies, rapid surface runoff, splash erosion and widespread sediment entrainment. On steep slopes, concentrated runoff initiated or enlarged gullies, forming V-shaped channels in unconsolidated or weakly consolidated deposits. Rapid degradation of gully sidewalls contributed additional sediment to the drainage network (Fig. 4A-B). Runoff and sediment were transferred downstream through both natural channels and artificial or newly formed flow paths. In several sectors, the stormwater drainage network became obstructed by sediment and urban debris, promoting overbank flow, avulsion of ephemeral channels and flooding of low-lying urban areas. In lower positions of the De La Quinta catchment, blocked drainage conduits and sediment-laden flows produced severe street flooding and accumulation of mud-rich deposits (Fig. 4D), a scenario replicated in other neighbors, such as Laprida (Fig. 4C).

The reduction in flow velocity within low-gradient urban depressions favored deposition of suspended and bedload material. In some sectors of the southern urban area, flood deposits exceeded 2 m in thickness, and their removal required nearly two months after the event. These deposits demonstrate that the 2017 flood was not only a hydrological disaster but also a major sediment-transfer event, in which ephemeral catchments delivered large volumes of sediment into the urban fabric.

Part of the water and sediment load reached the coastline, where temporary deltas up to 500 m in diameter developed at ephemeral-stream outlets. These short-lived depositional bodies indicate that exceptional rainfall events can transfer sediment from the catchment scale to the coastal system over

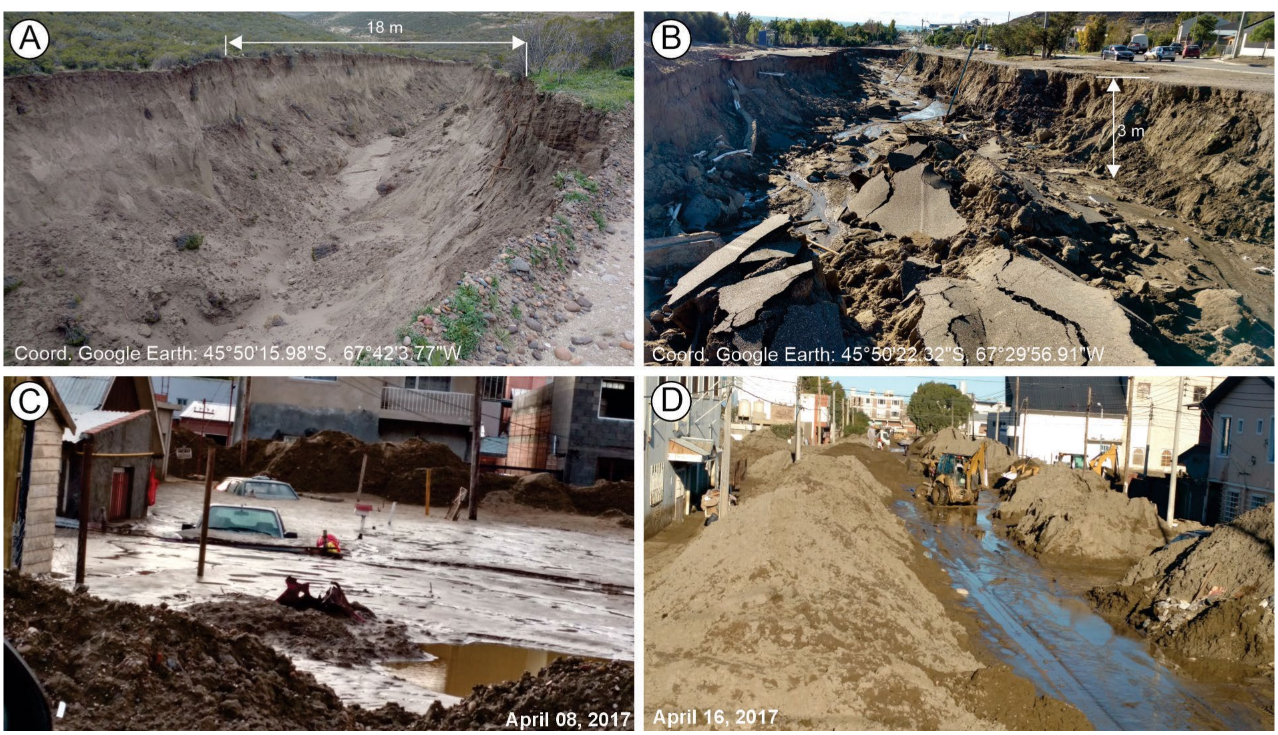

Figure 4. Erosional and depositional features associated with the March-April 2017 extreme rainfall event. (A) V-shaped gullies developed close to the headwaters in the De la Quinta basin. (B) Formation of deep gullies in steep urban areas. Fray Luis Beltrán Avenue, Km. 3 drainage catchment. (C-D) Sediment deposition in lowland areas of the (C) Laprida sub-basin and (D) De La Quinta catchment (location in Fig. 1B).

very short timescales. Their subsequent reworking by wave action links the flood system with coastal sediment dynamics, a connection that is further evaluated below.

Planned versus completed mitigation works in the De La Quinta catchment. The De La Quinta catchment was one of the most severely affected drainage systems during the 2017 flood. Its lower reaches drain toward the southern sector of Comodoro Rivadavia, where low-lying urban areas received large volumes of runoff and sediment during the storm. Because of this exposure, the catchment was selected for the development of flood-control infrastructure based on upstream sediment and runoff retention.

The proposed mitigation system consisted of four check dams, identified as R1, R2, R4 and R7, distributed along the main tributaries of the De La Quinta drainage network (Fig. 5A–C). The hydraulic rationale of the project was based on the simultaneous operation of these structures, with the objective of reducing flow velocity, retaining part of the sediment load and attenuating stormwater discharge before it reached densely urbanized downstream sectors. At present, only the R4 check dam has been completed and is operative (Fig. 5D–E). This structure is located near the entrance to the Los Tres Pinos neighborhood (Fig. 5C), in the lower-middle sector of the catchment. The remaining projected structures, particularly R1 and R2 in the upper catchment, have not been constructed. As a result, the current mitigation system does not reproduce the original design conditions, because runoff and sediment generated in the upper basin remain largely unregulated.

The spatial mismatch between the projected four-dam system and the single completed structure is a relevant result for evaluating residual flood exposure. The upper catchment areas controlled by the non-constructed R1 and R2 dams correspond to sectors with high relief and long flow paths, where storm runoff may acquire high velocity and sediment-transport capacity before reaching urban areas. Therefore, the present configuration reduces local hazard only partially and leaves downstream neighborhoods exposed to future high-magnitude rainfall events.

The comparison between planned and completed infrastructure also indicates that flood mitigation in Comodoro Rivadavia remains uneven among catchments. Outside the De La Quinta system, most drainage basins have not received comparable structural mitigation, except for localized channel rectification or isolated drainage works. This pattern reinforces the need to evaluate flood hazard at the scale of complete ephemeral catchments rather than only at individual urban drainage points.

Shallow landslides, slope reactivation and the Cerro Chenque failure

Urban slope instability in landslide-prone neighborhoods. Slope instability in Comodoro Rivadavia is concentrated in sectors where urban occupation overlaps with steep slopes, relict landslide deposits, weak lithological intervals and artificial modifications of drainage or slope geometry. The main urban settings affected by landslide-related processes include Barrio Sismográfica, slopes within the Km 3 and Km 4 drainage basins, the flanks of Cerro Chenque, and coastal cliffs between the Port of Comodoro Rivadavia and Chalet Huergo (Fig. 1C, Fig. 6).

Barrio Sismográfica represents one of the clearest examples of urban expansion over pre-existing unstable terrain. Historical aerial photography from 1970 shows a large landslide body in the sector, whereas recent satellite imagery shows progressive urban occupation over the landslide deposit and near its toe (Fig. 6A). This spatial overlap indicates that a geomorphic feature already recognizable before the main phase of urban occupation became incorporated into the urban fabric.

Instability in this neighborhood includes lateral spreading, rotational sliding, piping and subsurface erosion. These processes are favored by the presence of weak clay-rich lithologies, local groundwater circulation and cavities generated by water-driven erosion. The catastrophic January 18th, 2026, displacement event in the Sismográfica sector, located in the southern slope of the Hermitte Hill, was preceded by a 20-days creep stage and affected up to 450 houses emplaced either on top of formerly landslided materials or very close to the toe of the displaced volume. The 2026 Sismográfica landslide is currently under investigation, and its evolution will be analyzed in a separate paper. This event is relevant because it demonstrates that relict landslide deposits within the city cannot be treated as inactive geomorphic features when urban drainage, loading and water infiltration modify local stability conditions.

Additional slope failures occur in the Km 3 and Km 4 sectors. In the Km 4 neighborhood, small-scale failures were identified adjacent to irrigated public spaces located near steep slopes (Fig. 6B). In the Km 3 drainage basin, a medium-sized landslide occurred on April 10, 2017, two days after the end of the March–April extreme rainfall event (Fig. 6C). The timing of this failure indicates that slope response may be delayed relative to peak rainfall, consistent with progressive infiltration, pore-pressure increase and reduction in shear strength within weak intervals.

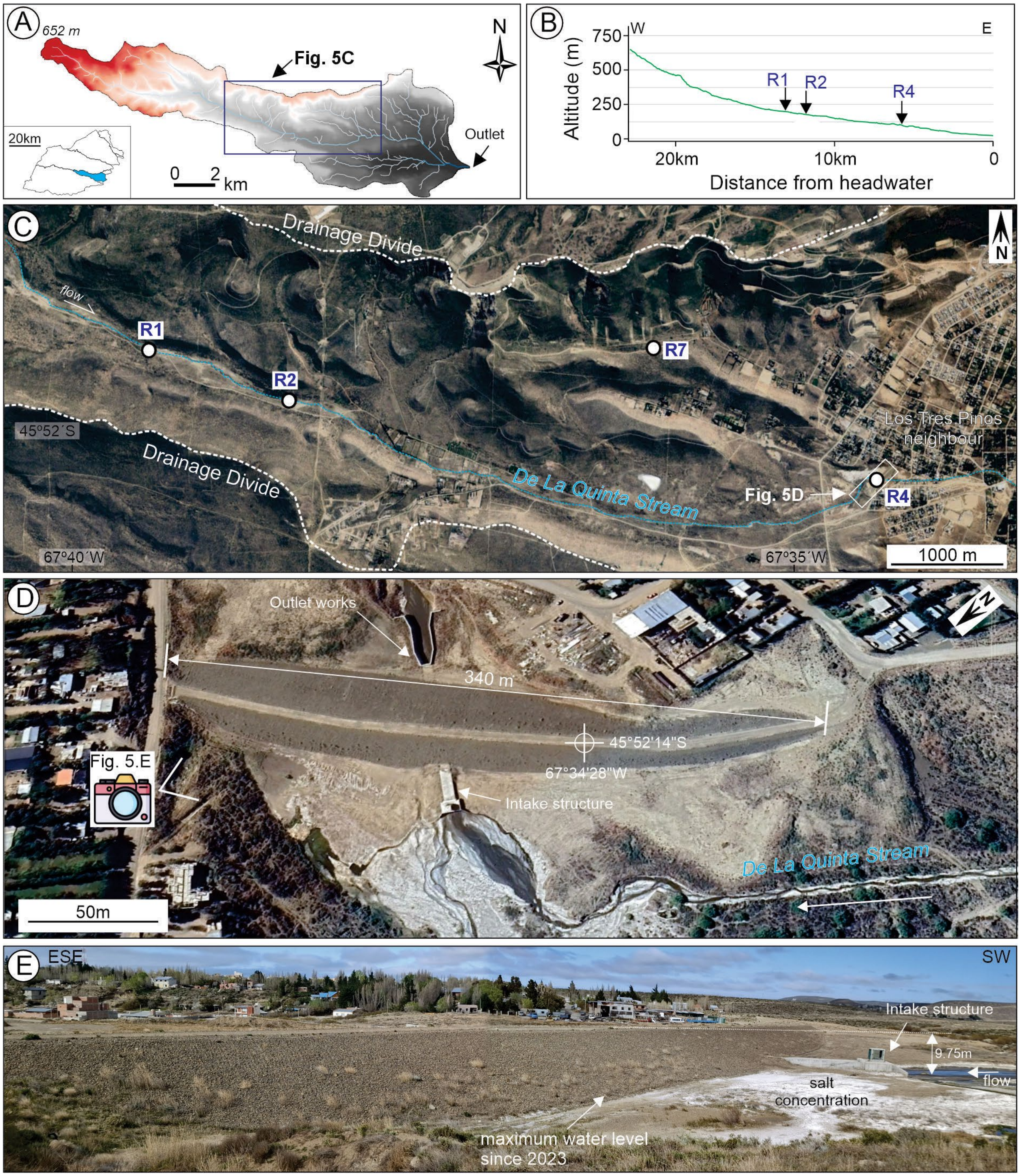

Figure 5. Projected and developed mitigation infrastructure of floods in the De La Quinta drainage catchment. (A) Topographic relief with a simplified drawing of the channel network. See the inset and Fig. 1.B for general location of the basin. (B) Slope of the longest stream of the Arroyo de la Quinta basin. (C) Projected check dams (R1, R2, R4, R7) along the main tributaries of De La Quinta basin. To date, only the R4 check dam is operative. (D-E) Check dam R4, emplaced at the entrance of the Los Tres Pinos neighborhood.

Anthropogenic controls on slope instability. Anthropogenic modifications are spatially associated with several unstable slope sectors in Comodoro Rivadavia. These modifications include slope-foot excavation, road cuts, building loads, artificial irrigation, deficient stormwater drainage, leakage from urban water or sewer networks, vegetation removal and surface disturbance related to urban and industrial infrastructure. Although the available data do

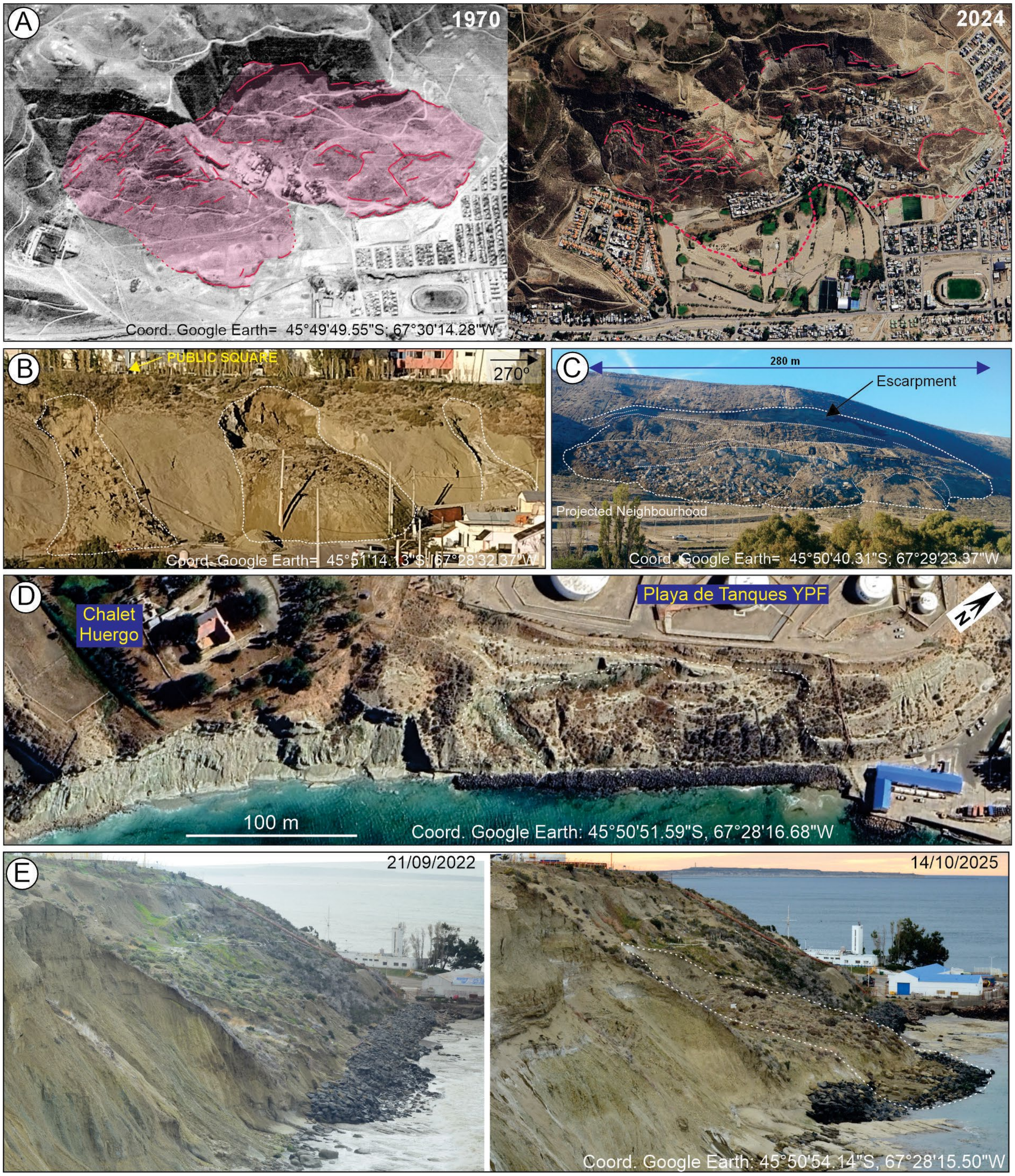

Figure 6. Landslides and their physiographic setting. (A) Aerial photography (year 1970) of the landslide in the Barrio Sismográfica, Km. 3 drainage basin. The satellite image at right (2024) shows urban growth over the landslide and at the toe. (B) Small-scale failures of slopes in the Km. 4 or 25 de Mayo neighborhood. The yellow arrow points to a public square located adjacent to the high-angle slope. (C) Medium-sized landslide in the Km. 3 drainage basin. The landslide occurred on a steep slope on April 10, 2017, two days after an extreme rainfall event. (D) Google EarthTM satellite image of the coastal area adjacent to the Playa de Tanques YPF and Chalet Huergo (Date=February 22, 2025). Notice the revetment at the toe of the cliff protecting the slope below Playa de Tanques YPF, and cliff retraction south of the protection. (E) Comparison of the revetment´s position at Playa de Tanques in 2022 and 2025, evidencing a recent landslide that reduced its effectiveness during storms.

not allow a city-wide quantitative factor-of-safety calculation, the mapped distribution of slope failures shows repeated coincidence between unstable terrain and human-induced changes in surface-water pathways or slope geometry.

Artificial irrigation is particularly relevant where public green spaces are located on or immediately upslope from steep slopes developed on low-permeability or clay-rich substrates. In such settings, repeated water input may increase soil moisture, promote seepage along permeable sandstone intervals and enhance instability along weak clay-rich horizons. The Km 4 slope failure shown in Fig. 6B illustrates this type of anthropogenic forcing, where an irrigated public square is located adjacent to a high-angle slope.

Slope-foot excavation and road construction also modify stability conditions by removing support from the base of hillslopes. This is significant in neighborhoods located along the margins of ephemeral drainage basins, where roads, houses and service infrastructure commonly occupy narrow corridors between channel margins and steep valley flanks. In these sectors, intense rainfall can simultaneously increase runoff, erode the slope toe and raise pore pressure within weak sedimentary intervals.

Coastal protection works introduce an additional anthropogenic control on slope instability. At Playa de Tanques YPF, a rocky revetment emplaced at the toe of the coastal cliff reduced direct wave attack for more than two decades (Fig. 6D). However, wave reflection and backwash contributed to the removal of beach sediment in front of the structure, exposing the more resistant substrate of the Sarmiento Formation. In September 2025, a landslide displaced part of the slope and affected the revetment at the toe (Fig. 6E). This case shows that coastal defenses may locally reduce marine erosion but do not eliminate slope instability where lithological weakness, steep relief and wave action persist.

Cerro Chenque: historical instability, stabilization works and 2023 reactivation. Cerro Chenque is the most critical landslide-prone landform within the urban area because of its position adjacent to the downtown sector, the coastline and National Route 3 (Fig. 7A). The hill reaches 212 m a.s.l. and is composed of alternating weak claystones and more resistant cemented sandstones of the Chenque Formation. This lithological arrangement favors differential erosion, rockfalls, rotational sliding and reactivation of older displaced masses (Fig. 7B).

The largest historical landslide affecting Cerro Chenque occurred in February 1995, when more than 150,000 m³ of material moved beneath National Route 3 (Hirtz and Blachakis 2000). The event involved fracturing of in-situ rock at the head of the movement, displacement of a large landslide mass and downslope propagation toward the coastal zone (Fig. 7D). Because National Route 3 is the main north–south transportation corridor through Comodoro Rivadavia and eastern Patagonia, this landslide had direct implications for urban and regional connectivity.

Subsequent stabilization works focused mainly on the southern flank of Cerro Chenque. These works included terracing, slope regrading, drainage structures and local reinforcement measures such as guniting and anchoring (Francisca et al. 2017). Terracing reduced slope angle and redistributed part of the gravitational load, while drainage works were designed to intercept and convey surface runoff downslope (Hirtz et al. 2019) (Fig. 7C). During the March–April 2017 rainfall event, the terraced southern flank did not generate the same level of mud accumulation and flooding in the downtown sector as would be expected from an untreated steep slope, indicating that the intervention reduced runoff and sediment-transfer impacts in that part of the hill.

In contrast, the eastern flank of Cerro Chenque remained highly exposed to marine erosion and landslide reactivation. On August 30, 2023, part of the formerly displaced mass associated with the 1995 landslide was reactivated, causing the closure of National Route 3 for 35 days (Fig. 7E). Topographic data collected by drone before and after the event indicate that the reactivation was preceded by a storm-surge episode on August 20–21, 2023, when a high tide of 5.10 m coincided with storm waves nearly 3 m high. This marine forcing eroded the intertidal depositional surface and intensified toe erosion at the base of the cliff.

Topographic differencing shows a reduction of nearly 1 m in the intertidal surface adjacent to the base of Cerro Chenque after the storm. A slip surface then propagated upslope from the eroded cliff base, producing a rotational movement that involved an estimated displaced volume of approximately 70,425 m³ (Fig. 7F). The resulting pattern of negative and positive elevation change defines a depletion zone upslope and an accumulation zone downslope, consistent with rotational–translational reactivation of an older landslide mass. The Cerro Chenque case demonstrates that landslide hazard in Comodoro Rivadavia is not controlled exclusively by rainfall. Marine erosion, high tides, storm waves and the persistence of older displaced masses can combine to reactivate slope failures in coastal sectors. This result links the landslide system directly with coastal forcing and urban transportation vulnerability.

Coastal erosion, PCR sedimentation and disruption of urban connectivity

Cliff retreat and erosional coastal compartments between PCR and Chalet Huergo. The coastal sector between the Port of Comodoro Rivadavia, Cerro Chenque, Playa de Tanques YPF and Chalet Huergo contain adjacent

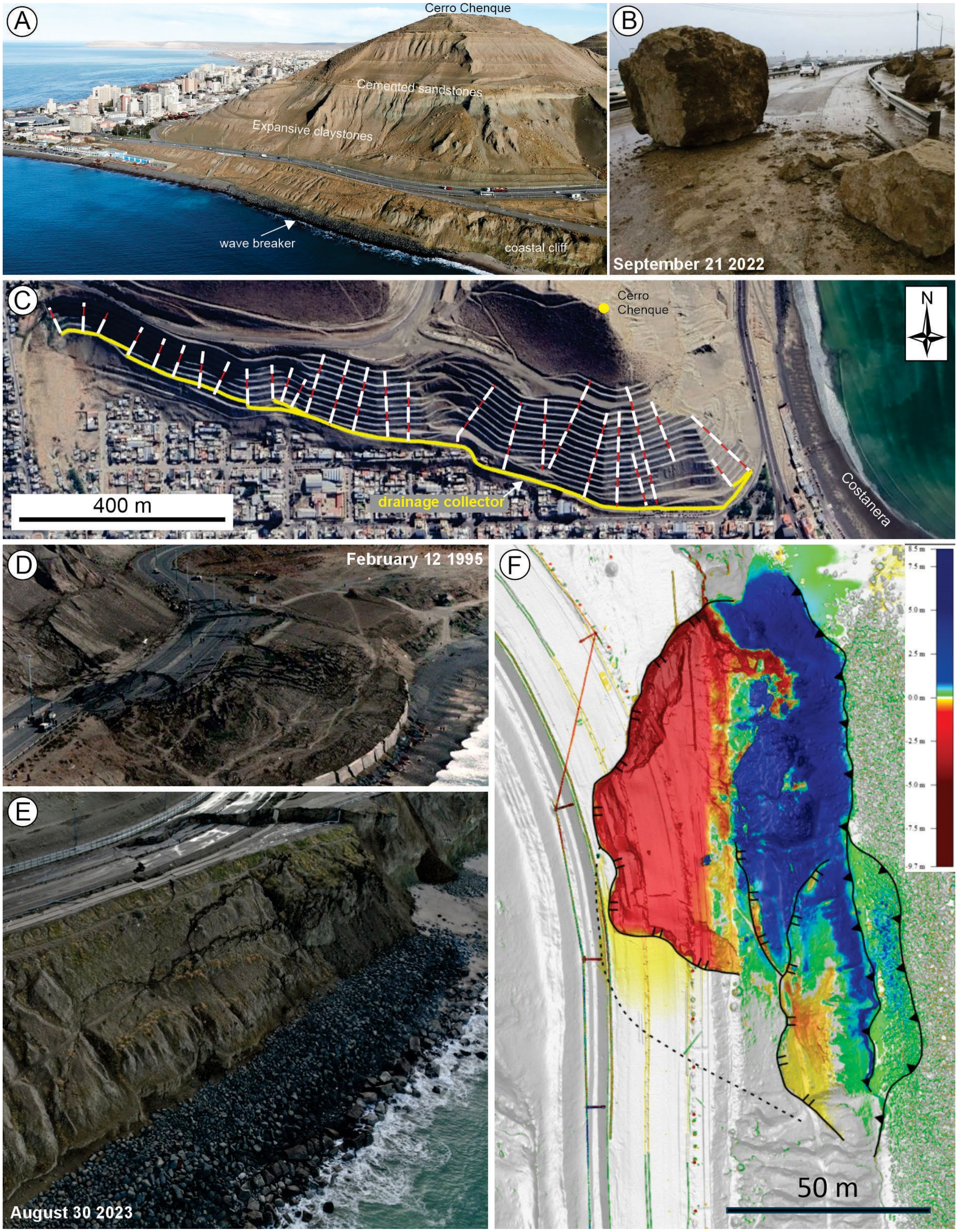

Figure 7. Cerro Chenque rockfalls and landslides. (A) Panoramic view of the Cerro Chenque and the coastal environment prior to the landslides of August 30, 2023. The National Route 3 is emplaced between the Chenque Hill and the coast. (B) Rockfalls of large blocks of consolidated sandstones are common after rainy events. (C) Terracing of the southern flank of the Cerro Chenque. This intervention has mitigated flooding in the city center and reduced the hill´s angle of repose. (D) Oblique view of the landslide of the eastern slope of the Chenque Hill, occurring in February 1995. (E) Oblique view of the landslide of August 2023, which remobilized part of the previous landslide. Coord. Google Earth: 45°51'20.10"S, 67°28'33.80"W (F) Relief differences of the landmass associated with the landslide of August 2023. Red and blue colors indicate downward and upward movement, respectively.

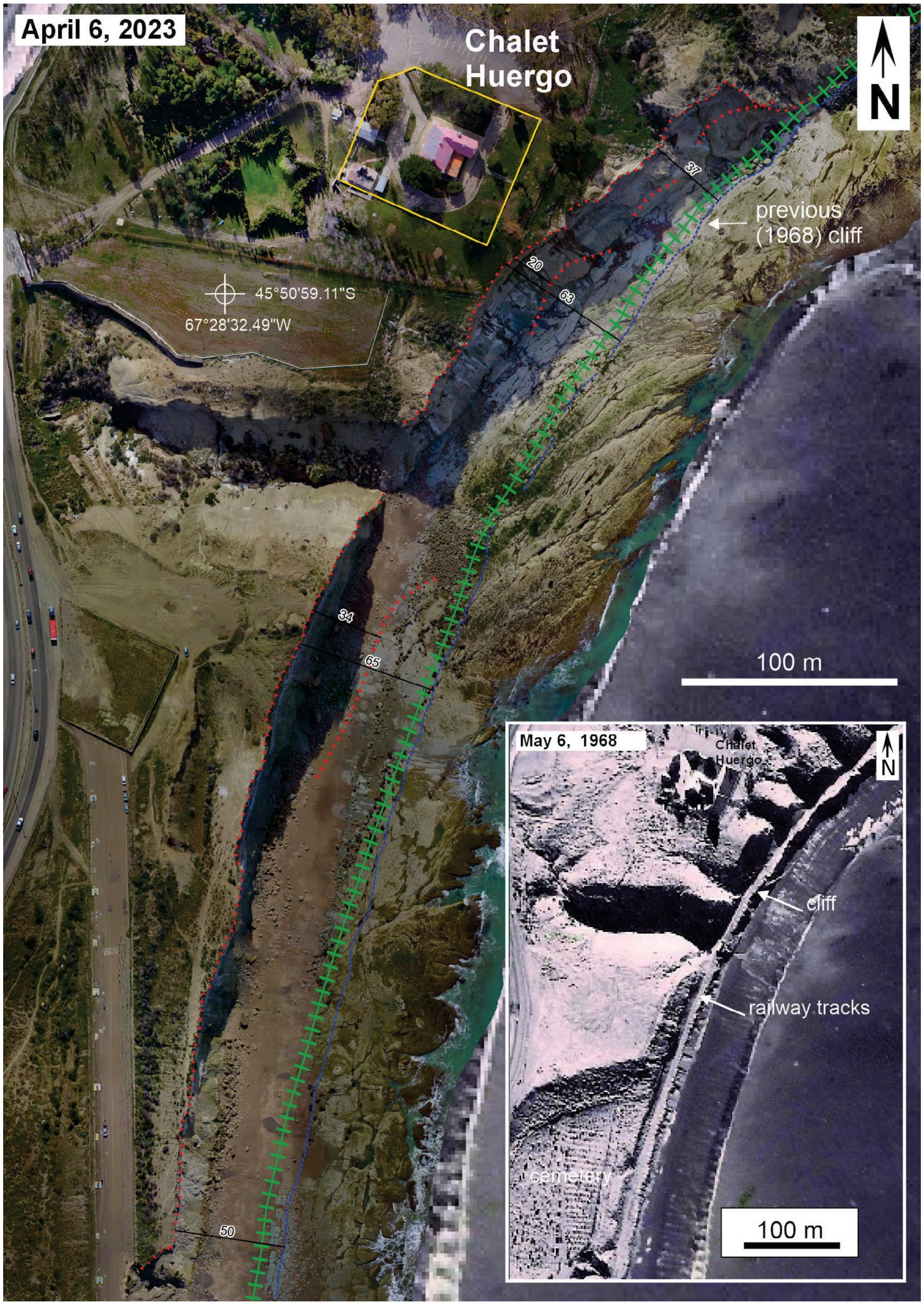

Figure 8. Location of coastal features from 1968 (inset) on a 2023 orthomosaic. The blue, green, and red dashed lines indicate the position of the shoreline, railway tracks, and cliff in 1968, respectively. The current cliff position is also shown. Measurements indicate the retreat of the cliff. Active marine erosion features are highlighted in their current location, including abrasion platforms, block falls, and active cliffs. Beach deposits are minimal. Cliff retreat rates range between 0.67 m/year and 1.18 m/year.

erosional and depositional compartments. The northern part of the bay is dominated by rocky shore platforms, active cliffs, block falls and narrow or discontinuous beach deposits, whereas the southern part includes depositional areas associated with the Costanera sector and the port.

Comparison between the 1968 aerial photograph and the 2023 orthomosaic shows significant cliff retreat along the coastal sector north of the port (Fig. 8). The former shoreline, railway tracks and cliff position were digitized from the historical image and compared with the current cliff edge. Measured retreat distances indicate spatially variable erosion rates, ranging from 0.67 m/year near Playa de Tanques YPF to 1.18 m/year in the central bay sector.

The highest retreat rates occur where active cliffs are directly exposed to wave attacks and where beach deposits are narrow or absent. In these sectors, abrasion platforms, block-fall accumulations and active scarps indicate ongoing marine erosion and gravitational instability. The presence of weak sedimentary intervals within the cliff-forming succession favors rapid degradation once toe support is removed by waves or storm surge.

Near Playa de Tanques YPF and Chalet Huergo, the coastline shows strong lateral variability over short distances. Protected sectors with rocky revetments display reduced direct erosion at the cliff toe, whereas adjacent unprotected or flanked sectors show accelerated retreat. This spatial pattern indicates that coastal defenses modify, rather than eliminate, erosional gradients along the cliffed shoreline.

Bathymetric change and sediment accumulation in the Port of Comodoro Rivadavia. Bathymetric records from the Port of Comodoro Rivadavia (PCR) reveal sustained sediment accumulation within the harbor area since the last major dredging operation in 1996. The port sector received more than 250,000 m³ of fine-grained sediment, mainly silt and clay, between 1996 and 2022. This accumulation reduced seabed depth by nearly 4 m in the Ultramar Port area and modified the morphology of the harbor floor (Fig. 9A–B).

Bathymetric cross-sections show that the infill body has an aggradational geometry. One longitudinal section, oriented approximately parallel to the main morphology of the infill, shows progressive vertical accretion between successive bathymetric surveys. A second SW–NE section shows the development of a flat-based, convex-upward sediment body that aggraded by more than 1.5 m after reaching the underlying bedrock surface.

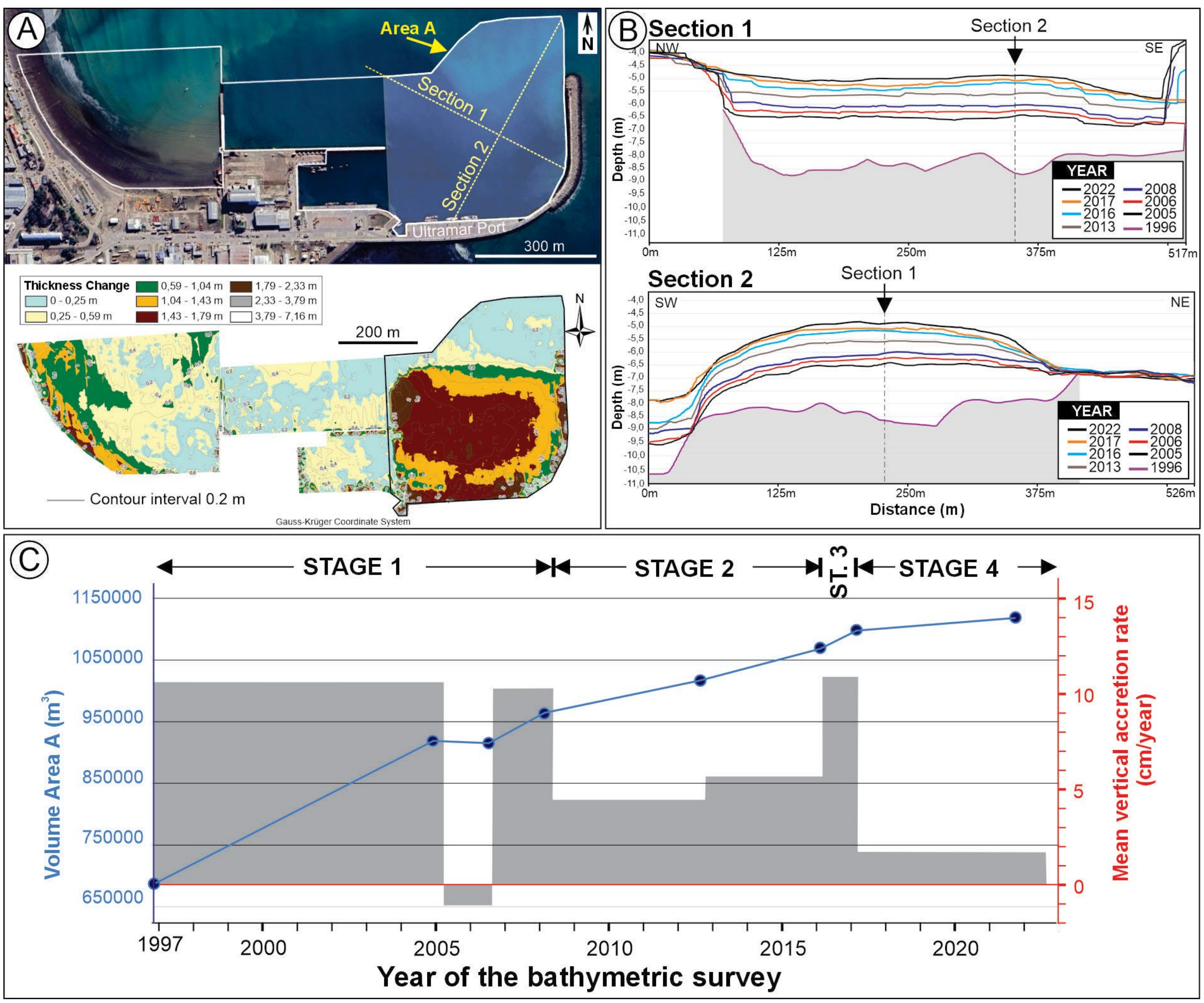

Figure 9. (A) Area of the PCR and local Costanera, with location of vertical cross sections in Area A. The map illustrates the thickness change between two bathymetric surveys in 2005 and 2022, evidencing an increase in the topographic surface (net aggradation rate) in the entire area, with maximum values in the upper berm of the Costanera and in the Ultramar Port. (B) Infill styles of the Comodoro Rivadavia harbor. Section 1 shows bathymetric changes between 1996 and 2022 along a direction approximately parallel to the general morphology of the infill, displaying an aggradational pattern. The SW–NE cross-section (Section 2), highlights the development of a flat-based, convex-topped body that has aggraded by more than 1.5 m after reaching the underlying bedrock. In both cross-sections, the 1996 topography is shown in grey. (C) Volume changes and vertical accretion rates in the Area A of the PCR. The data show a sustained increase in sediment accumulation in Area A, as reflected in the average vertical accretion rate between bathymetric surveys.

The temporal evolution of port infill can be divided into four stages (Fig. 9C). Stage 1, between 1996 and 2008, was characterized by relatively high vertical accretion rates of approximately 10 cm/year. Stage 2, between 2008 and 2016, shows lower aggradation rates, near 5 cm/year. Stage 3, between 2016 and 2017, records a marked increase in vertical accretion, with rates exceeding 10 cm/year, probably reflecting the incorporation of sediment associated with the March–April 2017 flood. Stage 4, between 2017 and 2022, shows lower accretion rates, below 2 cm/year, suggesting reduced net accumulation or partial sediment bypass under the post-2017 hydrodynamic configuration.

In the Costanera sector, topographic and sedimentological observations indicate accumulation of more than 4 m of gravelly-sandy material between 2005 and 2022 along upper beach berms. This accumulation contrasts with the erosional behavior of the cliffed northern sector and reflects the trapping of sediment in a lower-energy coastal compartment influenced by port structures, littoral drift and episodic sediment supply from ephemeral streams.

The combined bathymetric and topographic evidence indicates that the coastal system adjacent to the port receives sediment from multiple sources: longshore drift, reworking of cliff-derived material, drainage from urban slopes, ephemeral-stream discharge during rainfall events and artificial drainage from stabilized slopes. Therefore, the port area currently functions as a sediment sink within the urban coastal system.

Failure of coastal defenses and loss of road connectivity. Coastal erosion has directly affected urban connectivity in Comodoro Rivadavia. Several coastal roads and marginal transportation corridors are located only a few tens of meters from active cliffs or defended shorelines. Where rapid cliff retreat coincides with ineffective or deteriorating coastal defenses, road infrastructure is increasingly exposed to collapse, prolonged service disruption, and, in extreme cases, permanent abandonment.

The Ara San Juan coastal road, connecting the Km 3 and Km 4 sectors, provides a clear example of those processes (Fig. 10). During a storm in August 2023, waves attacked and overtopped the protective measures, and the flows over the revetment´s crest damaged the concrete seawall protecting the road. After the failure of the protective structure, waves rapidly eroded the cliff and road margin, making the coastal connection inoperative. The damaged sector shows displaced concrete blocks, active erosion scarps and progressive loss of the road platform.

The loss of the Ara San Juan coastal road reduced the redundancy of the urban transportation network. As a result, daily north–south movement through the city became more

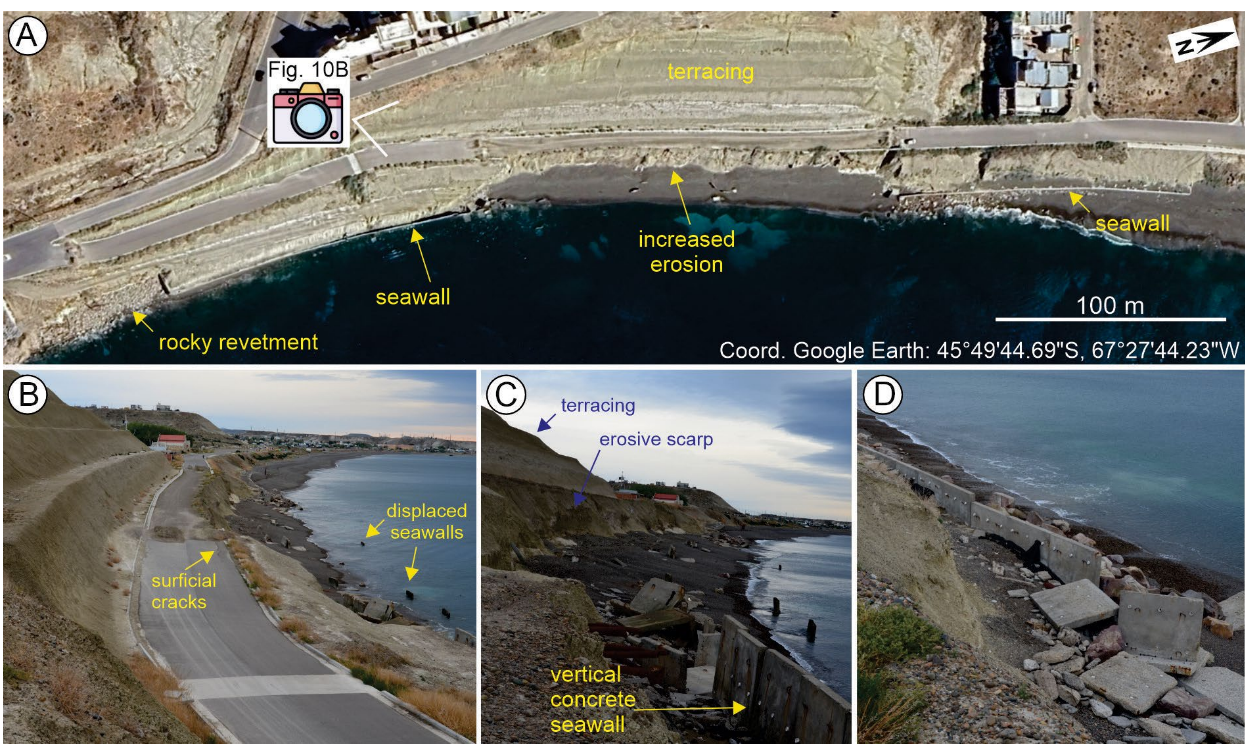

Figure 10. Reduction of traffic connectivity along coastal roads. (A) Failure of the “Ara San Juan” road by wave attack, occurred in August 2023. Google EarthTM image (February 20, 2025). (B-D) Images of the destruction of protective measures (concrete seawall) of the “Ara San Juan” Road, occurred by wave overtopping during a storm.

dependent on National Route 3, the same corridor affected by landslide activity at Cerro Chenque. This creates a cascading exposure condition: coastal erosion removes alternative marginal roads, while landslide reactivation threatens the main transportation corridor.

The 2023 coastal-road failure and the 2023 Cerro Chenque landslide therefore represent connected expressions of the same urban geomorphic problem. Marine forcing, cliff retreat, slope instability and infrastructure placement interact to reduce the functionality of transportation corridors in a high-relief coastal city. These results provide the empirical basis for the multi-hazard interpretation developed in the next section.

DISCUSSION

Ephemeral-catchment floods, sediment transfer and urban growth

The results show that flooding in Comodoro Rivadavia is not only a hydrological problem related to rainfall intensity, but also a geomorphological and consequently an urban-planning problem controlled by the coupling between steep ephemeral catchments, high sediment availability, urban occupation of low-lying areas and incomplete mitigation infrastructure. This interpretation is consistent with dryland fluvial systems, where channel activity is commonly episodic, discharge is concentrated in short-duration events, and sediment transfer may be strongly nonlinear relative to rainfall magnitude (Graf 1988, Tooth 2000). In such systems, low-frequency, high-magnitude storms may produce geomorphic work that greatly exceeds that of ordinary annual runoff, especially when antecedent dry conditions favor the accumulation of loose sediment in channels, hillslopes and urban surfaces.

The March–April 2017 storm represents the most extreme rainfall event documented in the instrumental record of Comodoro Rivadavia. Previous studies demonstrated that this event triggered widespread runoff, gully development, channel widening, overbank sedimentation, avulsion of ephemeral channels and the formation of temporary deltas at catchment outlets (Paredes et al. 2020, 2021). The updated rainfall record presented in this contribution indicates that the 2017 event remains an outlier in terms of daily rainfall and total accumulated precipitation. However, the occurrence of extreme post-2017 rainfall, particularly the September 2022 event, shows that the city continues to be exposed to high-magnitude rainfall episodes. Therefore, the main issue is not whether each individual event can be attributed directly to climate change, but whether the urban system is prepared to absorb repeated high-intensity hydrological pulses without reproducing the geomorphic and infrastructural impacts observed in 2017.

Urbanization modifies the hydrological response of ephemeral catchments through several pathways. Impervious surfaces increase runoff efficiency, road networks and stormwater drains concentrate flow, channel rectification modifies conveyance, and occupation of flood-prone corridors reduces the accommodation space available for sediment-laden flows. In this context, the high sediment load observed during the 2017 flood should not be interpreted as an anomalous feature of a single event, but as the expected response of a steep semiarid catchment network where natural sediment availability is enhanced by anthropogenic disturbance. Similar feedbacks between urbanization, peak runoff, channel erosion and sediment transfer have been described in human-modified fluvial systems, where land-use change alters both the magnitude and timing of geomorphic responses (Trimble 1997, Gibling 2018).

The De La Quinta catchment provides a clear example of the mismatch between catchment-scale hazard and partially implemented mitigation. The projected system of four check dams was designed to attenuate runoff and sediment transfer before flows reached densely urbanized lowlands. However, only the R4 dam is currently operative. This condition means that the catchment is not functioning as originally planned from an engineering perspective: runoff generated in upper-basin sectors remains unregulated, while downstream neighborhoods continue to depend on a mitigation system that is spatially incomplete. Therefore, the key discussion is not whether check dams are useful in principle, but whether partial implementation can create a false perception of reduced risk.

This situation highlights the need to evaluate flood mitigation at the scale of entire ephemeral catchments rather than through isolated structures. A catchment-based strategy should integrate upstream retention, preservation of natural drainage corridors, sediment-source control, maintenance of stormwater infrastructure, restriction of urban expansion over active flow paths, and restoration of vegetation cover where feasible. In Comodoro Rivadavia, the recurrence of extreme rainfall after 2017 indicates that flood-risk reduction cannot depend exclusively on emergency response or localized engineering works.

Slope instability as a coupled lithological, hydrological, marine and anthropogenic problem.

Landslide activity in Comodoro Rivadavia results from the interaction between inherited geological susceptibility and recent triggering or amplifying processes. The alternation of weak clay-rich intervals, tuffaceous deposits, permeable sandstones and more resistant cemented beds provides a stratigraphic architecture favorable to differential erosion, seepage, rockfall and slope failure (Tejedo et al. 2000, Cravero 2002). This type of lithological control is especially relevant in high-relief urban settings because relatively small changes in pore pressure, slope geometry or toe support may reactivate previously stable or dormant hillslope sectors. The observed instability in Barrio Sismográfica, Km 3, Km 4, Playa de Tanques YPF and Cerro Chenque indicate that landslide hazard is distributed across several geomorphic settings rather than restricted to a single slope.

Rainfall is an important trigger of slope instability, but the results indicate that it is not the only relevant forcing. The April 2017 landslide in the Km 3 basin, which occurred shortly after the extreme rainfall event, illustrates delayed hillslope response to infiltration and pore-pressure changes. This mechanism is consistent with rainfall-triggered landslide models in which failure may occur after peak rainfall if water infiltration progressively reduces shear strength along weak horizons (Gariano and Guzzetti 2016). However, the 2023 Cerro Chenque landslide reactivation demonstrates that marine erosion can also trigger or prepare slope failure by removing basal support. In this case, storm waves and high tide eroded the intertidal surface and cliff toe eleven days before the reactivation, directly linking coastal forcing with gravitational instability. This interpretation is consistent with documented mechanisms of coastal-slope instability, in which wave attack, storm surge and high tides enhance cliff-toe erosion, reduce basal support and promote the progressive failure or reactivation of pre-existing unstable masses (Doi et al. 2020). Wave-induced notch growth and cliff-base undercutting have likewise been shown to increase coastal-cliff instability and trigger rockfalls and mass wasting (Matsukura 2001; Rosser et al. 2013). In this context, the coincidence of storm surge, high tide and subsequent slope displacement at Cerro Chenque supports the interpretation that marine forcing acted as a direct trigger or, at minimum, as an immediate preparatory mechanism for landslide reactivation.

Anthropogenic activity modifies this natural susceptibility in multiple ways. Urban occupation over relict landslide deposits increases exposure, while artificial drainage, irrigation, leaking infrastructure, excavations at slope toes and building loads may modify local stability conditions. These controls are particularly important in the Sismográfica sector, where urban expansion has occurred over a pre-existing landslide body, and in Km 4, where irrigated public spaces are located near steep slopes. Although the available information does not allow a full quantitative factor-of-safety analysis for each slope, the spatial coincidence between unstable terrain and anthropogenic modifications indicates that urban land use is not a passive element of the hazard system. It acts as an amplifier of susceptibility and, in some cases, as a potential trigger.

The Cerro Chenque case is especially important because it shows contrasting outcomes of slope-management interventions. In the southern flank, terracing, drainage and stabilization works were implemented (Barletta et al. 2009; Francisca et al. 2017), reducing the sediment transfer and flooding toward the downtown area during the 2017 and 2022 storms. In contrast, the eastern coastal flank remained exposed to marine erosion, older landslide deposits and toe instability, culminating in the 2023 reactivation and closure of National Route 3. This contrast suggests that slope stabilization can be effective when it addresses the dominant process mechanisms, but it also shows that partial stabilization of one slope sector does not eliminate hazard at the scale of the entire hill.

The broader implication is that landslide risk in Comodoro Rivadavia should be managed as a dynamic and spatially distributed problem. Monitoring should not be limited to historically active scarps; it should include urbanized landslide deposits, irrigated or poorly drained slope margins, coastal cliffs with active toe erosion, and transportation corridors located downslope from unstable rock masses.

Coastal erosion, port sedimentation and sediment-budget redistribution

The coastal sector of Comodoro Rivadavia exemplifies an urban sediment-routing system in which erosion and deposition represent complementary components of a single sediment budget rather than independent geomorphic problems. Between the Port of Comodoro Rivadavia and Chalet Huergo, cliff retreat, abrasion platforms, block falls and narrow beaches define an erosional compartment, whereas the Costanera and port areas behave as long-term sediment sinks. This spatial organization is consistent with the sediment-budget concept, which considers coastal evolution as the balance between sediment sources, transport pathways and sinks within interconnected littoral cells (Rosati 2005, Bray et al. 1995).

Measured cliff-retreat rates of 0.67-1.18 m/year indicate that the northern part of the bay is undergoing rapid coastal erosion relative to the timescale of urban infrastructure. These rates are consistent with a coast where weak sedimentary units, narrow beaches, toe erosion and mass wasting interact to produce landward cliff migration. The presence of rocky revetments and seawalls modifies this pattern locally, but the Playa de Tanques YPF and Ara San Juan cases show that hard defenses may transfer erosion laterally, enhance wave reflection or fail during storm conditions. Similar studies from the Baltic Sea have demonstrated that eroding coastal cliffs constitute major sediment sources sustaining adjacent beaches and nearshore sediment budgets rather than isolated zones of land loss (Averes et al. 2021). Likewise, sediment-budget analyses from the eastern Mediterranean emphasize that cliff-retreat rates should be interpreted together with sediment production, transport efficiency and depositional sinks instead of considering shoreline retreat alone (Mushkin et al. 2019). These studies support the interpretation that the erosion observed along the northern sector of Comodoro Rivadavia represents an active sediment source feeding the adjacent coastal system rather than merely a localized hazard.

The accumulation of more than 250,000 m³ of fine sediment within the port between 1996 and 2022 indicates that the harbor functions as an efficient long-term sediment sink. Consequently, the infilling observed in Comodoro Rivadavia should not be interpreted solely as a maintenance problem but as the expected response of a modified sediment-routing system receiving sediment from both marine and terrestrial sources. The temporal coincidence between the major aggradation phase around 2016–2017 and the exceptional March-April 2017 flood further suggests that episodic sediment pulses generated by ephemeral catchments contribute substantially to the coastal sediment budget. Similar relationships have been documented along the Pacific coast of California, where a small number of extreme floods associated with climatic variability transport several decades' worth of sediment to the coast, dominating long-term sediment fluxes despite their low frequency (Inman and Jenkins 1999). More recent studies of coastal morphodynamics have likewise demonstrated that individual extreme events can reorganize coastal sediment budgets over timescales comparable to those of gradual shoreline evolution (Sherwood et al. 2022). These observations reinforce the interpretation that the temporary deltas documented after the 2017 flood (Paredes et al. 2021) likely represent significant sediment inputs subsequently reworked by wave action and incorporated into the nearshore and harbor sediment reservoirs.

Drainage works on the southern flank of Cerro Chenque reduces sediment delivery to downtown sectors but may simultaneously increase sediment transfer toward coastal sinks during intense storms. Similarly, PCR structures and coastal defenses can trap sediment locally while enhancing erosion in adjacent unprotected sectors. Similar responses have been recognized worldwide, leading to the adoption of sediment-cell and regional sediment-management approaches that evaluate engineering works at the scale of entire coastal compartments rather than individual protected sites (Rosati 2005, Thom et al. 2018).

Urban connectivity and cascading effects of geomorphic hazards

The geomorphic impacts documented in Comodoro Rivadavia are consistent with a cascading-hazard framework in which individual processes cannot be fully understood in isolation. Multi-hazard studies emphasize that hazard interactions may involve direct triggering, increased probability of subsequent events, or amplification through environmental and anthropogenic processes, and that ignoring these interactions can underestimate disaster risk or distort management priorities (Kappes et al. 2012, Gill and Malamud 2016). In the study area, extreme rainfall can trigger runoff concentration, gully erosion, sediment transfer, drainage obstruction, urban flooding and coastal sediment delivery, whereas storm waves and high tides may enhance cliff-toe erosion, promote landslide reactivation and disrupt transportation corridors. Similar approaches have been used to evaluate cascading or interacting hazards in urban and infrastructure-exposed settings (Dunant et al. 2021, Youssef et al. 2023), and at river–coast interfaces where fluvial floods can trigger secondary coastal geomorphic responses in anthropogenically modified environments (Arróspide et al. 2026). This supports the interpretation of Comodoro Rivadavia as an integrated urban geomorphic system in which flood, landslide, coastal-erosion and sedimentation hazards are coupled through process chains and shared exposure pathways.

This type of cascading impact is particularly significant in high-relief coastal cities. When alternative routes are limited, damage to a single road segment can propagate through the urban system by increasing congestion, emergency-response times and dependence on vulnerable corridors. In Comodoro Rivadavia, the coastal road network, the port area and National Route 3 are all located within geomorphically active zones. Therefore, transportation vulnerability is not only an engineering problem; it is a spatial expression of the mismatch between urban growth and active landforms.

The concept of cascading impact also applies to sediment and water transfer. Extreme rainfall produces runoff, gully erosion and sediment mobilization in upper catchments; sediment then moves through urban drainage corridors, blocks stormwater infrastructure, floods low-lying neighborhoods and reaches the coast; once delivered to the shoreline, it may be reworked into PCR areas or alongshore depositional zones. Similarly, marine storms erode cliff toes, destabilize slopes, damage coastal roads and may contribute sediment to nearshore sinks. These process chains show that flood, landslide and coastal hazards should not be assessed independently.

Implications for territorial planning in high-relief semi-arid coastal cities

From a planning perspective, the evidence provided in this research indicates that the most vulnerable sectors are not only those with high local hazards, but those where multiple process pathways intersect with critical infrastructure. Cerro Chenque, the Port of Comodoro Rivadavia, the De La Quinta outlet, the Sismográfica sector and the Ara San Juan Road are examples of such intersections. They combine geomorphic activity, urban exposure and limited functional redundancy. Future hazard assessments should therefore prioritize nodes where process coupling can generate disproportionate social or infrastructural impacts.

The results support a shift from reactive hazard management toward anticipatory territorial planning. Comodoro Rivadavia has a substantial body of geological, geomorphological and engineering knowledge documenting flood-prone catchments, unstable slopes and active coastal erosion. However, the persistence of urban occupation in low-lying outlets, landslide-prone slopes and retreating coastal margins suggests that scientific information has not been fully translated into land-use regulation, infrastructure prioritization or long-term urban design. Similar discrepancies between hazard knowledge and land-use regulation have been documented in coastal Chile, where planning instruments frequently fail to incorporate updated hazard information or climate-driven changes despite the availability of scientific evidence (León et al. 2023). Comparable institutional barriers have also been identified in disaster-risk governance elsewhere, where the challenge lies less in generating scientific information than in translating it into effective regulatory decisions (Ogra et al., 2021).

These observations support a development strategy based on geomorphic process domains rather than administrative boundaries. Active drainage corridors, depositional lowlands, landslide deposits, slope toes, cliff-top margins and coastal erosion zones represent functional landscape units with distinct levels of susceptibility that require differentiated land-use regulations and adaptive engineering standards. Similar approaches have been proposed in geomorphological hazard mapping, where landforms are used as the primary framework for spatial planning because they better represent the processes controlling future hazard evolution (Chelli et al., 2021). Likewise, coastal adaptation studies increasingly recommend the establishment of setback zones and dynamic planning areas that account for long-term shoreline retreat instead of relying exclusively on fixed administrative limits (Kirby et al., 2021). A multi-hazard planning framework for Comodoro Rivadavia should include at least five components. First, catchment-scale flood management should prioritize completion and maintenance of planned retention structures, preservation of drainage corridors and sediment-source reduction in upper and middle basins. Second, slope-risk management should combine monitoring, drainage control, regulation of irrigation and leakage, restrictions on slope-foot excavation and relocation or reinforcement strategies in sectors already affected by deformation. Third, coastal management should move from isolated hard defenses toward sediment-cell analysis, cliff-retreat setbacks, wave-energy dissipation and periodic evaluation of defense performance. Fourth, transportation planning should identify alternative corridors and protect critical nodes where landslides and coastal erosion can disrupt urban connectivity. Fifth, institutional coordination should ensure that municipal planning, PCR management, road infrastructure, hydrocarbon activity and scientific monitoring operate within a shared hazard-information system.

The case of Comodoro Rivadavia also has relevance for other semiarid, high-relief coastal cities. It shows that climate forcing, even when expressed through infrequent events, can produce large geomorphic impacts where urbanization has reduced the capacity of natural systems to accommodate water, sediment and slope deformation. It also shows that anthropogenic interventions may have ambivalent effects: check dams, terraces, drains, revetments and seawalls can reduce local hazards, but if they are incomplete, poorly integrated or disconnected from sediment-routing processes, they may create residual or transferred risks. Similar conclusions have been reached in international coastal management studies, which show that hard-engineering structures frequently redistribute rather than eliminate hazards by altering sediment transport, shoreline adjustment and coastal morphodynamics (Williams et al. 2018). Thus, resilience depends less on individual engineering structures than on the degree to which those structures are embedded in a process-based territorial strategy.

CONCLUSIONS

This study shows that Comodoro Rivadavia functions as an integrated urban geomorphic system, where flooding, landslides, coastal erosion, port sedimentation and disruption of urban connectivity are coupled processes rather than independent hazards. The city occupies a high-relief coastal setting in which steep ephemeral catchments, weak sedimentary successions, macrotidal dynamics, episodic high-magnitude storms and urban expansion over geomorphologically sensitive areas combine to generate multi-hazard conditions.

The updated rainfall record confirms the exceptional magnitude of the March–April 2017 storm, the largest event in the 1956–2022 instrumental series, with 399.4 mm of accumulated rainfall and 232 mm in one day. However, subsequent extreme rainfall events indicate that the vulnerabilities exposed in 2017 reflect recurrent exposure to low-frequency, high-magnitude storms capable of triggering rapid runoff, sediment transfer and infrastructure disruption. In ephemeral drainage basins, these events generate nonlinear geomorphic responses, including runoff concentration, gully erosion, channel widening, bank collapse, avulsion, drainage obstruction and sediment accumulation in low-lying urban areas. Flood mitigation remains incomplete, particularly in the De La Quinta basin, where only the R4 check dam is currently operative from an originally planned system of four structures. As a result, runoff and sediment generated upstream remain largely unregulated, emphasizing the need to evaluate mitigation works at the scale of entire catchments rather than as isolated interventions.

Slope instability is controlled by the interaction between lithological susceptibility, hydrological or marine triggers and anthropogenic modification. Alternating clay-rich, tuffaceous, sandy and conglomeratic intervals favor seepage, differential erosion, rockfalls and landslide reactivation, especially where urbanization occupies relict landslide deposits, slope toes or unstable hillslopes. These conditions are further amplified by irrigation, deficient drainage, leaking infrastructure, excavation and building loads. The Barrio Sismográfica, Km 3 and Km 4 sectors show that landslide-prone areas remain active components of the urban landscape, even when instability is inherited from older geomorphic processes.

The Cerro Chenque landslide illustrates the coupling between coastal forcing and slope reactivation. The 2023 movement, which affected part of the 1995 landslide mass, was preceded by storm waves and high tide that enhanced erosion at the base of the coastal slope. The estimated displaced volume of approximately 70,425 m³ and the 35-day closure of National Route 3 demonstrate that landslide hazards have direct consequences for urban and regional connectivity. Therefore, coastal slope instability must be managed together with marine erosion, storm-surge activity and the exposure of critical transport corridors.

Between the Port of Comodoro Rivadavia and Chalet Huergo, erosion and sediment accumulation occur within the same sediment-routing system. Cliff retreat rates of 0.67–1.18 m/year indicate active erosion along exposed coastal slopes, whereas bathymetric data show the accumulation of more than 250,000 m³ of fine-grained sediment in the port sector between 1996 and 2022. These contrasting trends suggest that coastal management should move beyond local defensive structures and consider sediment-cell behavior, cliff stability, port sedimentation and sediment supplied by both coastal erosion and episodic catchment discharge.

Overall, risk reduction in Comodoro Rivadavia requires process-based territorial planning within a multi-hazard framework that explicitly incorporates geological and geomorphological constraints. Priority actions include catchment-scale flood control, completion and maintenance of mitigation works, preservation of natural drainage corridors, regulation of construction on unstable slopes and cliff-top margins, monitoring of active landslide sectors and adaptive coastal management in areas of rapid cliff retreat. The case of Comodoro Rivadavia demonstrates that urban resilience cannot rely solely on isolated engineering works, but requires the integration of geological, geomorphological, hydrological, coastal and urban-planning information into long-term territorial decisions.

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