XXXVIII
IAH Congress

Groundwater Quality Sustainability
Krakow, 12–17 September 2010

Extended Abstracts

Editors:
Andrzej Zuber
Jarosław Kania
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University
of Silesia
Press 2010

abstract id: **331**

topic: **1**
Groundwater quality sustainability

1.3
Urban hydrogeology

title:

Evaluation of groundwater quality in the wide urban area of Cagliari (southern Sardinia, Italy)

author(s): **Giovanni Barrocu**
University of Cagliari, Department of Land Engineering, Italy, barrocu@unica.it

Fabrizio Staffa
University of Cagliari, Department of Land Engineering, Italy,
fabriziostaffa@hotmail.com

Maurizio Testa
Progemisa, Regional Government Agency, Italy, mtesta@arpa.sardegna.it

Gabriele Uras
University of Cagliari, Department of Land Engineering, Italy, urasg@unica.it

keywords: coastal aquifer, monitoring, contamination

INTRODUCTION

Urbanization has a great impact on underlying aquifers as groundwater quality and quantity may be endangered by human activities (Barret et al., 1997; Appleyard, 1995; Baiocchi et al., 2005; Barrocu et al., 1978).

The coastal aquifer beneath the Wide Urban Area of Cagliari, southern Sardinia, Italy (Figure 1) represents a typical case for studying the aquifer dynamics beneath an urbanized area.

The study area has a surface of 100 square kilometers with a population of about of 300,000 inhabitants, representing the 40% of the Sardinian population.

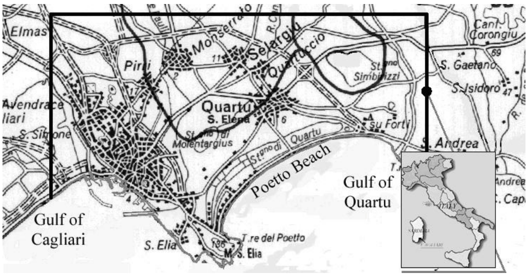

Figure 1. The study area.

The urban area of Cagliari is located in a promontory projected out to the south into the Mediterranean Sea. The promontory, bordered by the coastal ponds of Santa Gilla, to the west, and Molentargius, to the east, consists of ten hills emerging from the plain of Campidano, in the central part of the Gulf of Cagliari. In 1977, the coastal ponds were considered by the RAMSAR convention among the most important wetlands of the Mediterranean area. (Figure 2).

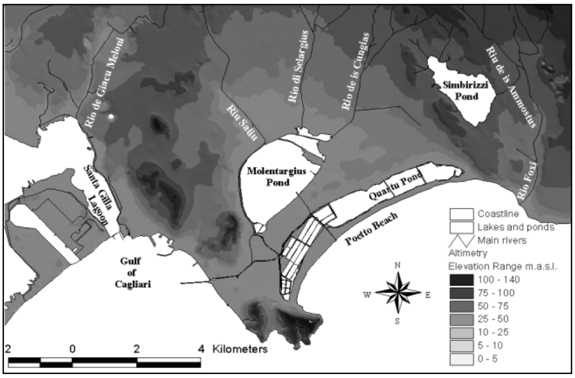

Figure 2. Morphology of the area.

The urban area sprawls from the central hills with their historical settlements to the surrounding plain as far as the slopes of the peripheral hills, pools and coastal borders.

GEOLOGY

The reliefs and the bedrock of the plain are made of a transgressive Miocene series named "Cagliari limestone" (upper Miocene: Tortonian), deposited on the southernmost part of the Sardinian rift in concomitance with the Alpine orogenesis (Santoro, 1970).

The stratigraphy of the urban area of Cagliari is represented in Table 1 (Santoro, 1970). The series consists from top to bottom of biothermal limestones ("Pietra Forte" Auct.), bioclastic sandstones ("Tramezzario" Auct.), and clayeous limestones ("Pietra Cantone" Auct.). The series overlays the "Pirri sandstones" (upper Miocene: Serravallian).

The Quaternary deposits are grouped into two depositional units, the "UBSU (Unconformity-Bounded Stratigraphic Unit) of Portovesme" (upper Pleistocene), and the UBSU of the Holocene deposits, including sediments of different depositional environments (beach, eolian, lacustrine deposits), and anthropic deposits (Barrocu et al., 1981). Hill slope lower parts are locally covered with quarry debris.

The Miocene series was affected and split by several fault systems in different tectonic blocks variously uplifted and depressed with maximum vertical displacements in the order of 200 m, so that the limestone banks of the "Pietra Forte" formation, representing the upper levels of the Miocene series, outcrop on the top of the tectonic blocks and are found a few meters below the present sea level. The ten hills of Cagliari, 76÷145 m high, represent the remnants of the blocks modelled by natural erosion processes and quarrying activities.

Table 1. The main geologic formations of the urban area of Cagliari.

CHRONOLOGY			MARINE, FLUVIO-LACUSTRINE AND LAGOON DEPOSIT	CONTINENTAL DEPOSIT
QUATERNARY	**HOLOCENE**	Actual	*"Formation of Santa Gilla and Molentargius Ponds and Port Formation"*	Quarry debris, artificial ground, sand e coastal dunes
	PLEISTOCENE			
		Würm		*"Red earths"*
		Tyrrhenian /Interglacial Riss - Würm	*"Panchina Tirrenica"*	*Loose "Terraced alluvium"*
		Milazzian II / Glacial Riss		*"Old Terraced alluvium", well cemented*
		Sicilian /Glacial Mindel	*Clays*	
		Emilian/Interglacial Günz - Mindel		
		Calabrian / Glacial Günz		
CENOZOIC	**PLIOCENE**	Villafranchian		*"Samassi Formation"*
	MIOCENE	Messinian	*"Pietra Forte"*	
		Tortonian	*"Tramezzarlo"*	
			"Pietra Cantone"	
		Serravallian	*"Pirri Sandstone"*	
		Langhian	*"Fangario Clay"*	
		Aquitanian	*Marl*	

The hilly land and coastal plain of Cagliari and its surroundings are the final part of a complex hydrographic network system which drains the "Campidano plain" to the north, the mountains of Sulcis to the west and the Sarrabus to the east of the urban area. Many of its original geomorphological features are preserved and have strongly affected regional planning and town development.

The hill of Castello–Buon Cammino is limited to the east by a vertical and locally overhanging cliff 12÷20 m high, representing the visible part of a fault plane, belonging to the fault system which displaced the Miocene series of the area of Villanova in a set of secondary blocks degrading towards the plain bordering y the west the coastal pool of Molentargius. The "Pietra Forte" is locally very fractured and karstified.

Empty spaces due to natural porosity and underground excavations in the carbonatic series, such as ancient cisterns, wells, rock chambers and WWII bomb shelters caused local settlements which seriously damaged building foundations and structures. Relief cliffs experienced serious rockfalls over the centuries, and were considered officially unstable till the 1980's (Barrocu et al., 1981), when a long series of remedial works to prevent rockfalls and erosion were started and eventually carried out, so that slopes are now stabilized.

Underground excavations started in prehistorical times and became systematic in the Punic period. The "hypogean rooms" the large necropolis of Tuvixeddu, one of the most important of the Mediterranean region. were used both as dwellings and tombs. Most of them were destroyed by quarrying dimension stones and limestones for mortar and industrial cement production. Some hypogean tombs of the necropolis were destroyed in the II century b. C. by the Romans, who tunneled through the area with their underground aqueduct system, one of the most important construction of their time in Sardinia. From the necropolis the aqueduct branched out in several canals and pipelines in tunnels to supply water to the ancient quarters of Karalis (Cagliari) (Santoro, 1970).

CLIMATE

The Campidano plain is characterized by a Mediterranean-maritime climate with the maximum rainfall in the winter, generally between November and January, and minimum rainfall, generally in July and August, with great differences between monthly high and low peaks, as shown in Figure 3.

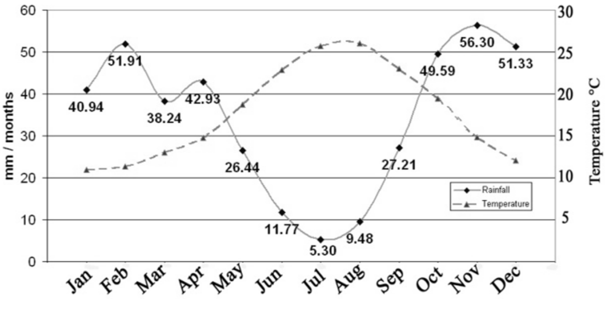

Figure 3. Average rainfalls and temperatures (1974–2003).

In order to determine the average rainfall in the study area, we considered the pluviometric stations of "Cagliari S.I." (7 m a.s.l.), "Settimo" (65 m a.s.l.), "Sestu C.ra" (48 m a.s.l.) and "Corongiu Aqueduct" (126 m a.s.l.), with a significant period of observations (at least 30 years) from

January 1974 to December 2003. Rainfall and temperature data were provided by the "Nuovo SISS" (New Study of the Surface Hydrology of Sardinia, 1921-1992), and the "Office of Civil Engineers of the Cagliari District" (1993–2004).

The average monthly rainfall was calculated as a weighted average taking into account the influence area for each station. The average yearly rainfall in the area is 410,70 mm, quite lower than the regional average of nearly 780 mm/y) and the national average of nearly 950 mm/y (average rainfall recorded in the period 1950-2000, APAT source). This situation is essentially due the low altitude of the area (only some meters above sea level), and its exposition to the dominant north-west dry wind.

As for the temperature, only the two stations of "Cagliari S.I." and "Corongiu Aqueduct" have been considered: the average annual temperature 17,7°C was calculated for January 1974–December 2003 (Figure 3).

In order to determine the net rainfall, the evapotranspiration, which at the latitude of the study area is an important element of the hydrologic balance, has been considered.

The real evapotranspiration Er was assessed with L.Turc's formula, modified by Santoro [8] for the hemi-arid region of the Mediterranean area

$$Er = \frac{P_a}{0.9 + \frac{P_a^2}{L^2}}$$

where:

P_a — is the average annual rainfall (1974–2003);

$$L = 586 - 10 \cdot T_C + 0{,}05 \cdot T_C^3$$

and T_c is the annual average daytime temperature in Celsius degree corrected to take rainfall into account. This value is obtained with the equation

$$T_c = \frac{\left(\sum_{1}^{12} P_i \cdot T_i\right)}{P_a}$$

where P_i and T_i are respectively the monthly average rainfall and temperature from 1974 to 2003.

The average *Er* values for each Thiessen polygon is shown in Table 2. The average annual evapotranspiration *Er* = 227.06 mm/y for the area was given by the weighted mean considering the weight of each polygon area.

Table 2. Evapotranspiration (1974–2003).

Pluviometric Station	Area [km^2]	T_C	L	Er [mm/y]
Cagliari S.I.	51.20	15.61	430.661	226.849
Settimo S.Pietro	41.19	15.53	431.439	227.236
Sestu (C.ra)	5.22	15.68	430.018	226.626
Corongiu (Acq.)	3.99	15.00	436.773	228.546

This quantity is around the fifty percent of the total annual rainfall so that a potential net rainfall of only 183.64 mm/y is available for recharging groundwater. Of course, the real infiltration rate is much lower given the large extension of the impervious surfaces of the plain, heavily urbanized, and the steep slopes of the hills free from constructions. In agreement with literature data for urban areas of semiarid regions a groundwater recharge value reduced to the 40% of that amount was considered for the water budget, i.e. 43.5 mm/y (Lerner, 2002).

HYDROGEOLOGY

On account of their high porosity, the limestones of the “Pietra forte” formation constitute a very permeable karstic aquifer, whereas the permeability of the underlying “Tramezzario” formation is very low and the clayeous limestones of the “Pietra Cantone” at the bottom of the calcareous series are practically tight.

The main aquifer (Mulas et al., 2005) is represented by the soft sandstones of the “Arenarie di Pirri” formation, underlying the limestones of the hills and an overburden of varying thickness in the surrounding plain.

A great deal of groundwater recharge is likely due to seepage from sewerage and pipeline networks.

Groundwater once used for drinking purposes is presently endangered by nitrate pollution mainly in the eastern part and saltwater intrusion by the coast, so that at present it is only exploited for irrigating city gardens and flowerbeds, and locally for heat pumps.

The eastern plain, once occupied by orchards and gardens, was intensively urbanized, so that locally the aquifer, once phreatic, became confined or semiconfined. Groundwater invaded several basements and the signs of water rise are visible in the foundation walls of many buildings.

METHODOLOGY

The reliability of the data available for the wells known in the urban area was verified, and the following information was updated and collected for each well: position (latitude, longitude, altitude), technical data (type of well, drilled or excavated, depth, geometric dimensions and casing), use (discharge rate and use period), physical and chemical data (hydraulic head, temperature, electrical conductivity, pH and TDS), pictures of the external structure and, where possible, other general information (type of aquifer, stratigraphy, owner, previous chemical analysis and historical information). All data were inserted in the GIS database, in order to locate wells, control altitude, type of aquifer, geology, land use (Corine land cover, 1993), and all kinds of information already updated in the database. A well monitoring network was then established with a grid of 1 well/km^2. Where water could be sampled. Wells had to be working, well hydrogeologically-defined, and, above of all, easily accessible. Thus, 39 wells could be selected.

In order to evaluate water quality, in agreement with the technicians and chemists of Progemisa (the regional agency in charge of the chemical analysis), the sampling campaign was organized to determine the following parameters indicated by the national law DLgs n.152 11.05.99 (updated with DLgs n.258 18.08.2000 and the D.Lgs n.152 03.04.2006): temperature (°C), total hardness (mg/L $CaCO_3$), electric conductivity (µs/cm (20°C)), bicarbonate (HCO_3-mg/L), calcium (Ca^{2+} mg/L), chloride (Cl^- mg/L), magnesium (Mg^{2+} mg/L), potassium (K^+ mg/L), sodium

(Na^+ mg/L), sulphate (SO_4^{2-} mg/L), ammonium ion (NH_4^+ mg/L), iron (Fe mg/L), manganese (Mn mg/L) and nitrate (NO_3^- mg/L).

All sampling was completed in less than two weeks, from May 10, 2006 to May 22,.2006, and in order to ensure the quality of the samples, they were kept in a portable fridge and delivered to the chemical laboratory within a few hours so as to ensure a good hydrogeological correlation (Mulas et al., 2005).

The following determinations were made by Progemisa (the Regional Government Agency — Chemical Laboratory and Material Experimentation — Regione S. Giovanni Miniera 1, Iglesias, CA):

- volumetric analysis (Cl^-, HCO_3^- and total hardness);
- spectrophotometry in the visible (NH_4^+ and NO_3^-);
- ICO-OES (ICO-Optical Emission Spectometer) (K^+, Na^+, Ca^{2+}, Mg^{2+}, SO_4^{2-}, and Mn);
- gravimetry (TDS);
- pHmetry (pH) ;
- conductimetry (CES and EH).

Chemical data were elaborated with AquaChem.

The input of this software is given by the chemical and physical data, geology, lithology and general information ; the output is a general report (anions-cations balance, dissolve minerals, etc.) and a “drinking water Regulations” report (SAR, ESR, Magnesium Hazard etc.) for each sample, as well as chemical charts (e.g. Durov, Piper, Schoeller, Stiff).

The classification prescribed by the law 152/99 for the “monitoring and classification of groundwater” was adopted. The groundwater was classified considering seven parameters, called “macro-describers”, which may give an idea of groundwater quality. These parameters are *electrical conductivity*, *chloride*, *manganese*, *iron*, *nitrate*, *sulphate* and *ammonium ion.* The general class of the sample is determined by the worst parameters found in the chemicals analysis.

This way, all data were arranged in four classes, ranking from 1 (the best condition) to 4 (the worst condition) plus a 0 class. The characteristics defined by each each class are as follows:

- *Class 1*: null or negligible human impact with precious hydrochemical characteristic;
- *Class 2*: reduced human impact, sustainable over long periods with good hydrochemical characteristics;
- *Class 3*: important human impact with general good hydrochemical conditions, and a few signs of degradation;
- *Class 4*: relevant human impact with poor hydrochemical characteristics;
- *Class 0*: null or negligible human impact with particularly natural hydrochemical facies and concentrations above Class 3 values.

RESULTS AND DISCUSSION

The first survey was carried out at the end of the summer 2005 in a network of 96 wells and 10 piezometers, where hydraulic heads, electrical conductivity, pH temperature, and organoleptic characteristics (colour, turbidity, smell) were determined.

As shown in the map of Figure 4, in large areas of the plains bordering the ponds of Cagliari and Molentargius the piezometric surface is 1÷2 m deep. The piezometric contour lines drawn on the basis of the water levels put clearly in evidence a watershed crossing the city of Cagliari in direction NNW-SSE, from the "colle San Michele", to the "Monte Urpinu". According to the morphology (Figure 2), groundwater flows from the hills to the pond of Santa Gilla, in the western part of Cagliari, directly to the sea in the central part, and to the pond of Molentargius in the eastern part.

The results of the chemical analyses carried out on groundwater samples show critical situations throughout the area. In particular, 29 samples were included in class 4, 6 in class 3, only 4 in class 2 and none in class 1.

Groundwater resulted affected by widespread contamination due to sulphates and local contamination due to ammonium, manganese and iron. The presence of nitrate (Figure 4) is almost surely caused by wastewater leakage. Nitrate concentration was high in two wide areas, in the oldest and most populated part of Cagliari, to the west of the watershed crossing Cagliari by the San Michele hill to the promontory of Cala Mosca, in the northeastern side of the Molentargius pond, by the historical centres of the towns of Selargius, Quartucciu, and Quartu Sant'Elena.

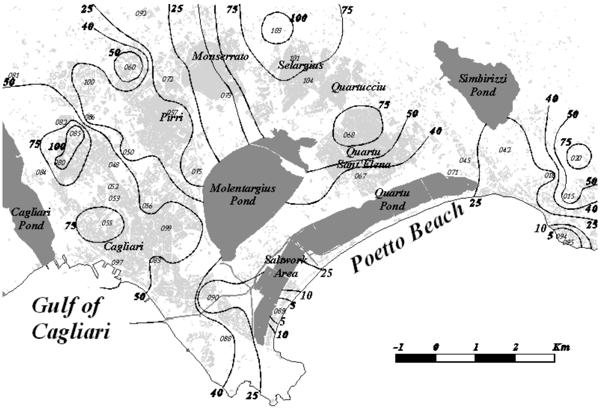

Figure 4. Piezometric map (m a.s.l.) (September–October 2005)

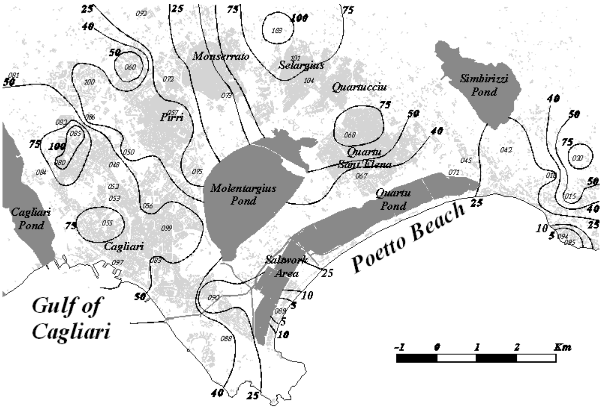

Figure 5. Isonitrate contour lines (values in mg/L).

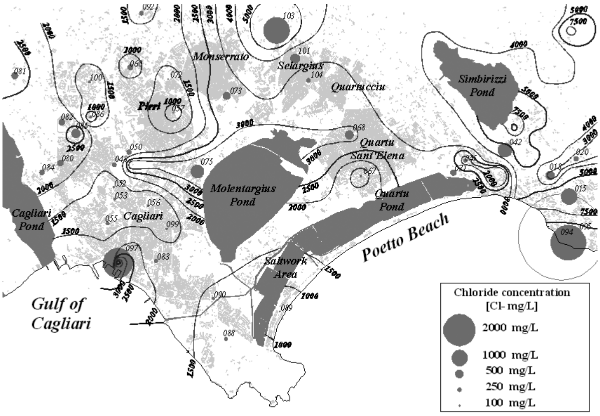

Figure 6. Isoconductivity [μS/cm] and chloride concentration.

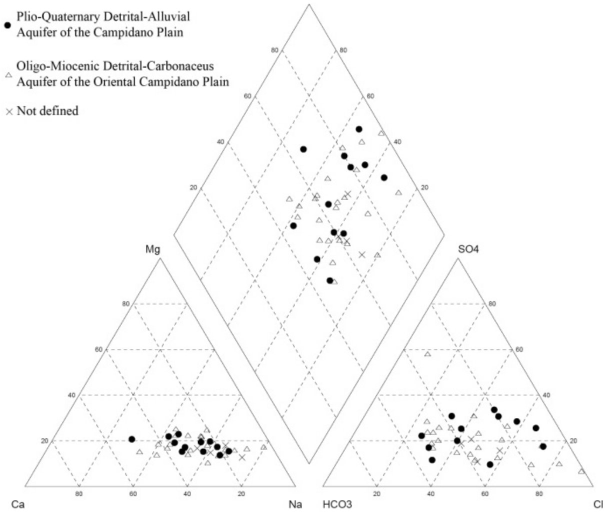

Figure 7. Piper hydrogeochemical diagram. Water samples are distinguished per type of aquifer.

Furthermore, the whole coastal area is affected by high chloride concentration locally due in various measure to lateral salt water intrusion from the sea, and upconing of old connate groundwater and recent groundwater leaching salty sediments.

The Piper hydrogeochemical diagram shows that groundwater samples mainly belong to sodium-bicarbonate, calcium-bicarbonate, sodium-chloride, and calcium-chloride facies (Figure 7). A few samples indicate sodium or calcium dominance with respect to anions. The hydrochemical facies of CaCl, NaCl, and sodium and calcium facies without anion dominance types, which have chloride contents higher than 150 mg/l, indicate the presence of salinization phenomena due to seawater intrusion (Appello, Postma, 1994).

The hydrochemical facies of NaCl and $NaHCO_3$ type with chloride contents lower than 150 mg/l, indicate that some parts the aquifer are subject to flushing of salinized sediments by fresh waters. Some samples pertain to bicarbonate-calcium facies, typical of fresh waters.

If we consider only the wells in the most intensively urbanized area, samples show a geochemistry with no dominance, as shown in Figure 8.

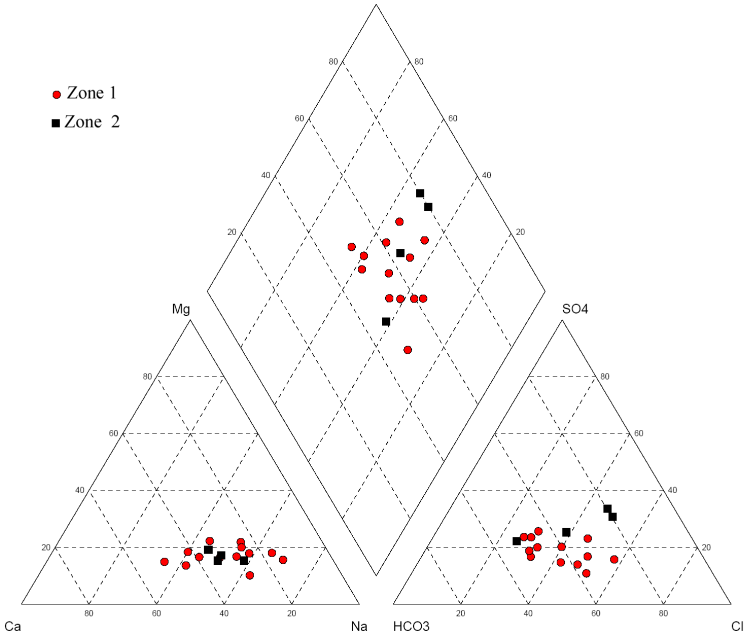

Figure 8. Piper hydrogeochemical diagram, for the sample in the higher urbanized area.

On the whole, the aquifer seems subject both to seawater intrusion and refreshing processes, while part of the aquifer is not affected by salinization.

CONCLUSIONS

The quality of groundwater in the area of Cagliari is generally influenced by urbanization: the more intense and old the urbanization, the worse groundwater quality.

The presence of nitrate is almost surely caused by wastewater leakage, the origin of the high chloride concentration in the whole area has not been clearly defined yet.

To the northeast of the study area, where marl formations are present, the high saline concentration may be due to their salt contents rather than to seawater intrusion.

Finally, the behavior of conductibility and chloride concentration matched with the high nitrate concentration in the more urbanized area could be justified by the recharge of groundwater by seepage of sewerage networks and pipelines. this fact could explain the lack of geochemical dominance for the majority of the samples.

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2-vol. set + CD
ISSN 0208-6336
ISBN 978-83-226-1979-0