Study of sediment dynamics in the Jordan River–Lake Kinneret contact zone using tracer methods

BORIS SHTEINMAN, DAVID WYNNE
Kinneret Limnological Laboratory, Israel Oceanographic and Limnological Research, Tiberias 14102, Israel
e-mail: b_shtein@ocean.org.il

YURY KAMENIR
Life Sciences Department, Bar Ilan University, Ramat Gan 52900, Israel

Abstract Sedimentation processes in the Jordan River–Lake Kinneret contact zone were studied using radioactive, magnetic and fluorescent tracers (RT, MT, FT, respectively). The natural RT method is based on the differences in natural radioactivity of river and lake sediments with different mineral composition. The natural MT method uses the magnetic properties of natural sediments. The FT method uses fluorescently tagged sediment particles placed on the bottom. Field measurements in the Jordan River mouth zone have shown that practically all the sediment (75%) brought by the river is deposited along a 100 m path from the river mouth. The sedimentation rate, measured using tracer methods, agrees well with rates obtained from a theoretical model that describes changes in concentration of suspended particulate matter along the jet flow in the river mouth.
Key words alluvial sedimentation processes; Jordan River mouth; tracer methods

INTRODUCTION

Erosion processes in basins of mountain rivers such as the Jordan River are very intensive. During floods, very high quantities of sediments are brought by the Jordan River to Lake Kinneret. These sediments reach the lake as suspended matter and as bed load transport. Our measurements have shown that the suspended load usually accounts for 95% or more of the total sediment discharge (Shteinman & Inbar, 1995). During floods, the bed load discharge reaches large values comparable to the suspended load. It should be noted that there are gravel and pebbles on the riverbed, about 500 m upstream from the river mouth. However, due to the decreased slope of the river bottom and the decreased flow velocity, their movement is restricted to that zone. They are practically not transported into the lake. With almost no sedimentation in the mountain part of the river, the suspended particulate matter (SPM) goes to the river mouth, which serves as the end point of the river transit. This process results in the formation of accumulative forms of relief, such as a mouth bar and spits, at the river–lake contact zone (RLCZ). The bar stability is a result of a dynamic quasi-equilibrium. Some sediments are removed by the waves and currents, but the river alluvium influx compensates for this loss.

The river–lake contact zone is often beyond the scope of both riverine hydrology and limnology. Hence, the sedimentation processes in this zone (RLCZ) are much less studied than those of the river or the lake. This is due to the fact that the flow hydrodynamics here are different from both the riverine and lacustrine regimes. The main specific property describes the river mouth flow as a free jet flow inside "liquid boundaries", and in the zone beyond the bar as a flow over the "liquid bottom".

When the river flow enters the accepting reservoir (sea or lake), it gradually loses its channel flow properties. The shore influence comes to an end and the water surface slopes diminish, with a decrease in the influence of gravity (or, more precisely, a decrease in its component parallel to the water surface). Beyond the river mouth bar the slope of the water surface becomes negligible, and the turbulent flow becomes inertial. These processes have been observed in the river mouth zones of many rivers (Mikhailov, 1971, 1997; Ibad-Zade & Shteinman, 1971; Shteinman, 1971) and have a practically universal character.

As a result of very intensive sedimentation processes, patches of river alluvium of various sizes are formed on the bottom, with more or less well-delimited areas. The most effective methods for study of such patches are those based on tracers, for which a short review is given below.

This paper provides results of studies of the accumulative processes in the Jordan River mouth, in the region of its entrance into Lake Kinneret, obtained using several tracer methods.

Site description

The Jordan River begins at the foot of Mount Hermon. Its length is about 360 km, its watershed surface is about 3000 km^2, and the mean water discharge is about 0.6 km^3 per year. The hydrological regime of the river is characterized by heavy rainfalls and floods. Some 90% of the annual water and sediment runoff occurs within the flood period, December–February.

Lake Kinneret is located in the "Jordan" region of the Syrian–African rift valley, in the northeastern part of Israel, 209 m below mean sea level (b.m.s.l.). It is a warm, monomictic lake with a surface area of 170 km^2, with maximum and average depths of 42 m and 24 m, respectively. The water level varies between 208.9 and 213.0 m b.m.s.l., limits authorized by the Water Commissioner (Serruya, 1978; Gophen, 1993). The Kinneret is the only natural freshwater lake in Israel and is used for recreation, tourism, commercial fishery, and water supply. The lake supplies annually about 25% of the country's freshwater consumption, including 50% of the drinking water demand. Therefore, water quality is of prime national importance (Gophen, 1993; Berman, 1985).

Within its mouth area, the Jordan River retains its mountain river properties, with slopes of up to 50 cm per km, and the riverbed is formed by coarse gravel. Only within the last kilometre before the entrance to the lake, does the water surface slope diminish by 5–6 times, the flow becomes calmer and the channel bottom is formed by sand–silt sediments. The depths along the river midstream are less than 1 m, but during flooding increase to 3–4 m, with flow velocities during these periods >2 m s^{-1}.

The river mouth has one arm. The delta, formed in the Jordan–Kinneret contact zone, protrudes some 100 m into the lake, and ends with a moon-shaped bar connecting the ends of the spits formed either side of the mouth (Fig. 1). The body of the bar is formed by clay and silty mud; its length is some 50–70 m (depending on sediment runoff) and water depths near the bar crest are less than 1 m.

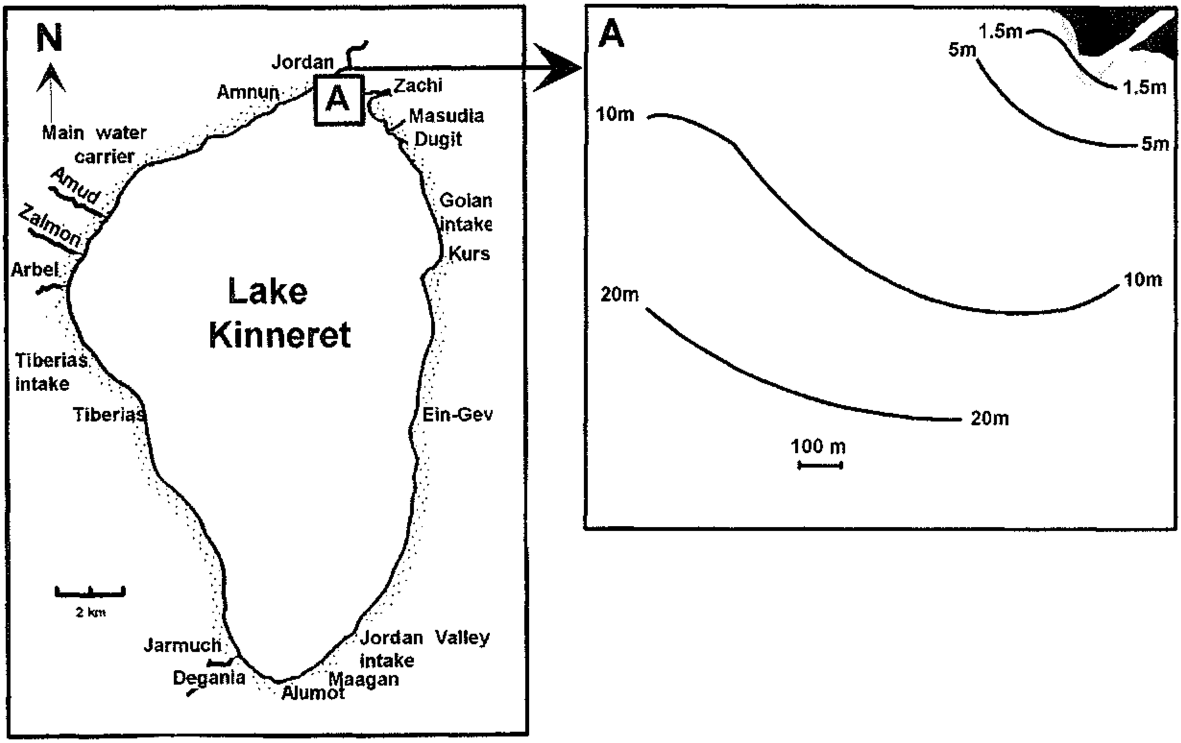

Fig. 1 Maps of the Jordan River–Lake Kinneret contact zone.

Existing tracer methods

Tracer methods were used to study the processes of sedimentation and redistribution of river alluvium in the Jordan River–Lake Kinneret contact zone. These methods are based on the following principle: marked materials, moving with the sediments, give information about the direction and velocity of their movement, so providing means of both qualitative and quantitative analysis (Kilpatrick & Taylor, 1986; Schmidt *et al.*, 1989; Shteinman, 1994).

Radioactive tracers (RT) with artificially induced activity This method consists of radioactive labelling of natural sediment particles. Such tracers are widely used for studies of sediment dynamics in the littoral zone of the sea and many river mouths, for various applied problems (IAEA, 1968; Albarede, 1997; Yelgaonkar *et al.*, 1997; Dahlgaard *et al.*, 1995). These methods use mountain rock containing heavy minerals, glass, resins and other materials to produce tracers. The material is crumbled to particles of the necessary size and then irradiated in a nuclear reactor; for resins, a technology of adsorption of radioactive isotope from a solution was developed. A complete review is given by Ibad-Zade (1978) and Gaspar (1987).

Another group of methods is based on applying radioactive labels to the surface of natural sediments (usually sand). There is a rather complicated method for putting such labels on particles of silt.

Use of RT provides a number of advantages: the measurement tools are sensitive enough to detect even very small concentrations of RT and the tracer properties are resistant to external impacts. At the same time, use of artificial RT is limited by application of very complicated technical means (for RT transportation and loading), legal limitations, personnel health hazards and environmental pollution. Therefore, ways to use natural radioactive properties of sediments for tracer production have been sought.

Natural radioactive tracers This method is based on the existence of differences in the natural radioactivity of sediments from a river, lake or sea, with different mineral composition. As a rule, river alluvium has a higher intensity of gamma radiation than do lake sediments, because of the higher concentration of the potassium isotope ^{40}K (Fig. 2). Because of this difference, it can be used as a natural tracer for the investigation of sediment transportation from the river to the sea or lake.

Natural radioactive properties of sediments for tracer measurements have been used, primarily, for studies of sediment movement in river mouths and brackish water (Kamel & Johnson, 1963; Martin *et al.*, 1970; Andersson *et al.*, 1992; Shteinman, 1971, 1994; Shteinman *et al.*, 1992; Rostan *et al.*, 1997). Such measurements were carried out in the river mouths of the Caspian Sea basin (Shteinman, 1971; Ibad-Zade, 1978) and in the mouth of the Jordan River entering Lake Kinneret (Shteinman *et al.*, 1992; Shteinman, 1994).

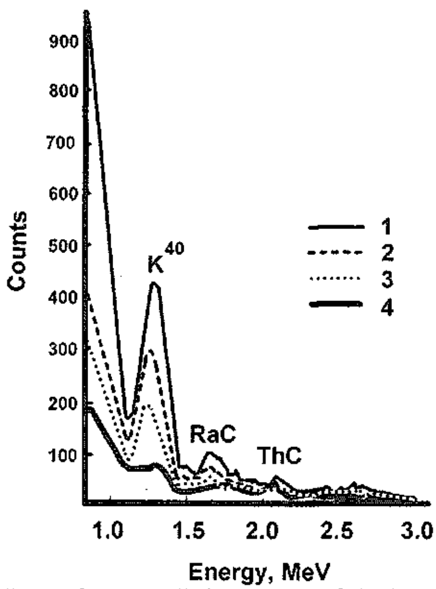

Fig. 2 Gamma-radiation spectra of the bottom sediment in the Jordan River–Lake Kinneret contact zone, 50, 100, 300 and 2000 m from the river mouth (curves 1–4, respectively).

Artificial magnetic tracers (MT) The MT method is based on the fact that magnetic probes, weighted on the bottom, register disturbances in the local magnetic field. Such disturbances permit us to follow the sediment movements *in situ* (Pantin, 1961; Bunte & Ergenzinger, 1989; Hassan, 1990; Ferguson *et al.*, 1996). To prepare artificial magnetic tracers, magnetic dust is applied to particles covered with a collodion. This method is not hazardous, which is a significant advantage over the artificial RT method. Nevertheless, the MT method has some drawbacks, such as the low resistance of the magnetic coating to abrasion, sticking of particles together, and a number of other processes changing the hydrodynamic properties of tracer particles.

Natural magnetic tracers Tracing of sediment dynamics by use of the natural magnetic properties of sediments is based on their magnetic susceptibility (Khesin & Shteinman, 1995; Karbassi & Shankar, 1994), characterized by their intensity of magnetization, *I*.

Rocks are usually magnetized by the Earth's magnetic field according to the *k* value. In accordance with the general classification, all substances fall into three categories:

- Diamagnetic substances ($k < 0$) which acquire an induced magnetization in a direction opposite to the magnetic field strength. Among these are water, salt, precious metals, graphite as well as quartz, orthoclase, calcite, barite, anhydrite and gypsum. Values of *k* for diamagnetics are very small.
- Paramagnetics ($k > 0$) are magnetized along the direction of the acting field. Among these are many rock-forming minerals: amphiboles, pyroxenes, olivine, chlorite, epidote. Values of *k* for paramagnetics are small and do not exceed a few hundred units (a unit is 10^{-5} SI).
- Ferromagnetics ($k >> 0$) are of very high magnetic susceptibility. Among these are magnetite, a-haematite, titanomagnetite and some varieties of pyrrhotite. The most abundant is magnetite (Fe_3O_4). Magnetization of the majority of rocks and ores depends mainly on their magnetite content (often magnetization varies in direct proportion to magnetite content).

The range of *k* value is very wide, from values near zero for most sediments to 0.1 unit SI for some gabbro and basalt as well as for pyrrhotite ore. Values of *k* for magnetite run to 10 units SI. Differentiation of the magnetic properties of rocks makes geological mapping and survey possible.

The coarse fraction of sediments, which contains eroded magnetically-active rocks, has a relatively higher magnetic susceptibility. Therefore it is possible to make *k* measurements to map the spatial distribution of river sediments when they are transported into the sea or lake.

Fluorescent tracers (FT) The artificial FT method is based on the use of fluorescently tagged sediment particles placed on the river bottom. Bed load samples, taken from the river or the lake bed after some time interval (days or weeks), are then analysed for their content of fluorescently labelled particles. The method of FT preparation and measurement has been described in detail by Shteinman *et al.* (1998). The use of natural fluorescent properties of some materials (e.g. some pigments) for tracing is not considered here, because as a rule artificial FT are used for studies of sediments dynamics in river–sea contact zones. For more information on this method see Gaspar (1987) and Kilpatrick & Taylor (1986).

MATERIALS AND METHODS

Three methods were selected for studies of the sediment dynamics at the Jordan River–Lake Kinneret contact zone: natural RT, natural MT and artificial FT.

Gamma spectra of bottom sediments (natural RT) were obtained using a 3X3" NaI well type detector and measuring system developed in the Van De-Graaf Accelerator Laboratory, Department of Physics, The Technion, Haifa (Koren *et al.*, 1982). Magnetic susceptibility (natural MT) was determined using a K-2 kappa-meter manufactured by SCINTREX (Canada). Artificial FT were prepared and used as described previously (Shteinman & Inbar, 1995; Shteinman *et al.*, 1998).

The studies were carried out during 1993–1995 on the transects described below. Loading of fluorescently tagged particles (artificial FT; 300–500 kg per experiment) was carried out at the Jordan River mouth gauge. Several measurement series were done in calm weather, to exclude the impact of waves and currents on the sedimentation processes. Part of the probe collection was also done after storm events to study the transfer of river sediments and their accumulation zones.

RESULTS

The alluvial sedimentation areas, determined from use of several tracer methods in the RLCZ along several transects, are presented in Fig. 3 for several dates in 1993–1995. Results obtained using natural RT, natural MT, and artificial FT correlate rather well and provide quite comparable estimates.

Four zones can be noted inside the alluvia sedimentation area:

- A zone of maximal gamma-activity in bottom sediments is delimited by an isoline of the ^{40}K isotope concentration in the sediments of 1.8 relative units (Fig. 3, column 1). The magnetic susceptibility (MS) values were also maximal ($\geq 2000\ 10^{-6}$ SI units) inside this zone (Fig. 3, column 2). Maximal concentrations of FT were registered at the same place (average of 10^{-10}–10^{-20} relative to the FT concentrations at the river mouth gauge) (Fig. 3, column 3). The estimated area of zone 1 is about 0.03–0.05 km^2.
- A zone of high gamma-activity in the bottom sediments, delimited by an isoline of the ^{40}K isotope concentration in the sediments of 1.4 relative units (Fig. 3). The magnetic susceptibility values inside this zone are $\geq 1000\ 10^{-6}$ SI units. Mean concentrations of FT were about 10^{-20}–10^{-30} relative to their initial concentrations at the river mouth gauge. The estimated area of zone 2 is about 0.2 km^2.
- A zone of elevated gamma-activity of bottom sediments, delimited by isolines of the ^{40}K isotope concentration in the sediments of 1.2 relative units. It is characterized by magnetic susceptibility values $\geq 750\ 10^{-6}$ SI units, and mean FT concentrations of about 10^{-50} relative to their initial concentrations at the river mouth gauge. The estimated area of zone 3 is about 0.5 km^2.
- A zone that is unaffected the Jordan River alluvium, is located further from the river mouth. ^{40}K concentrations and MS estimates are within the characteristic limits of natural "background parameters", i.e. about 1.0 relative unit and magnetic susceptibility $\geq 500\ 10^{-6}$ SI units, and mean FT concentrations of about 10^{-30}–10^{-40} from their initial concentrations. The estimated area of this zone is about 1 km^2.

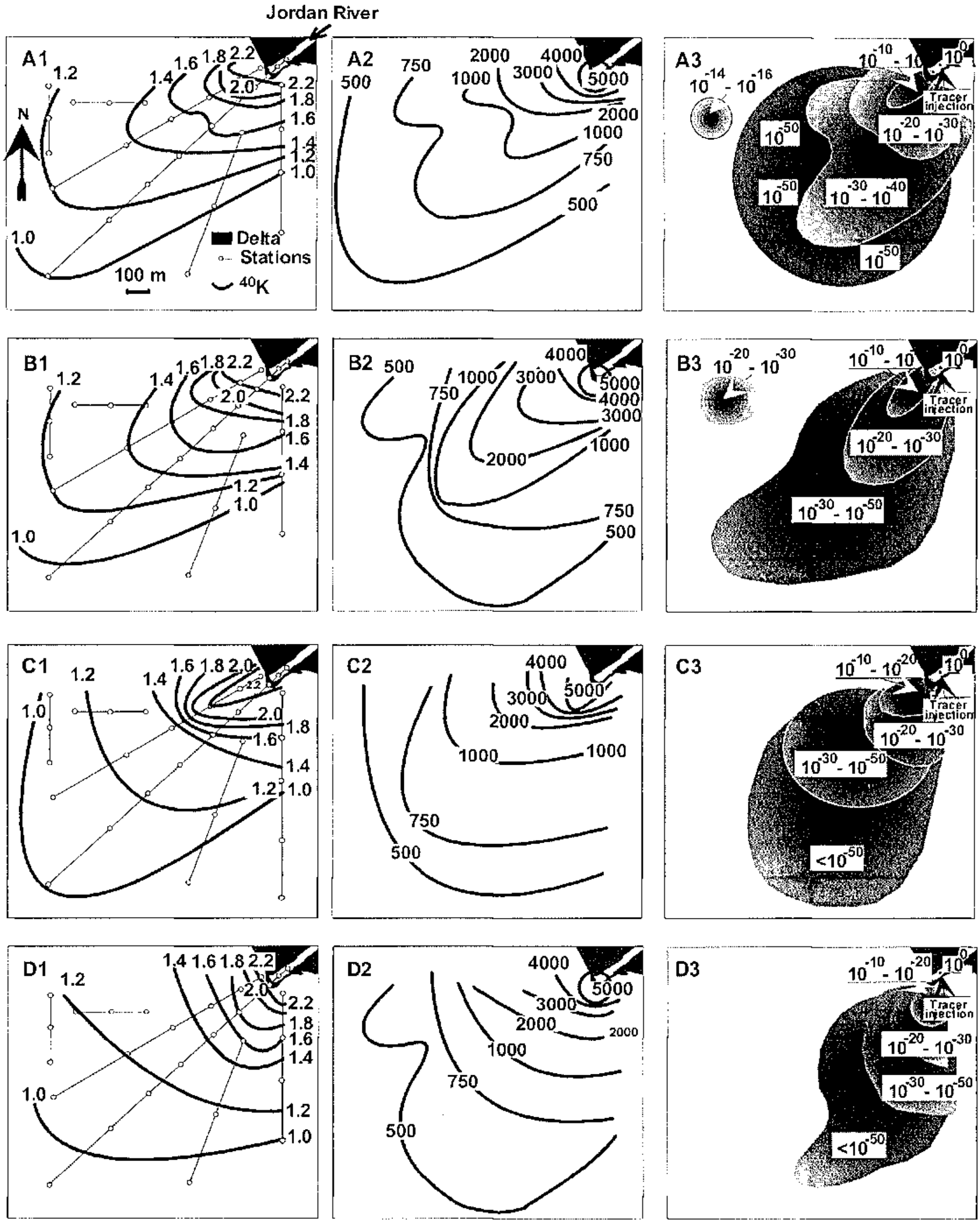

Fig. 3 Deposition areas of alluvium brought by the Jordan River and determined in the river mouth by tracer methods on transects and measurement stations. A1, B1, C1, D1: intensity of natural gamma-radiation of bottom sediments, shown as isolines of the ^{40}K isotope concentration (relative units); A2, B2, C2, D2: magnetic susceptibility isolines (10^{-6} SI units); A3, B3, C3, D3: fluorescent tracer concentrations. A = 16 February 1993; B = 21 February 1994; C = 18 March 1995; D = 24 March 1995.

The estimates obtained were based on studies carried out using the three methods described above (Fig. 3). However, the location and size of the patches depend on the suspended load in the Jordan River and the velocity and direction of the wind in the river mouth area. Therefore, they have some variability (Hadas *et al.*, 1996). During storm events, previously deposited sediments are redistributed by the waves and currents to a larger area of about 6 km^2 (Shteinman, 1994).

The field measurements have shown that during strong winds a large part of the sediments is translocated. About 80% of the sediment transport goes to the south, in a zone of depth less than 5 m. This long shore flow runs out to a distance of about 5 km from the river mouth. The sedimenting particles mainly supply the shore accumulation but a part of them is taken to the deep zone by the rip currents. This process produces small local patches of sediments on the bottom of the deep zone.

Formation of the river alluvia patches of various sizes on the lake bottom is linked to the process of SPM sedimentation along the jet flow (Shteinman & Kamenir, 1998). Decrease of the suspended particulate matter concentration along the jet flow (Fig. 4) results from two mechanisms: SPM sedimentation, and dilution of the river water with lake water. The first process predominates in the zone from the river mouth gauge out to the bar, when the river jet flows between the mouth spits. The second process (i.e. dilution) predominates beyond the bar crest when only the finest SPM fractions (0.005–0.010 mm), with negligible sedimentation velocities, are left in the jet. Therefore, intensive sedimentation takes place within the first 100 m range and produces the river alluvia patches of comparable dimensions.

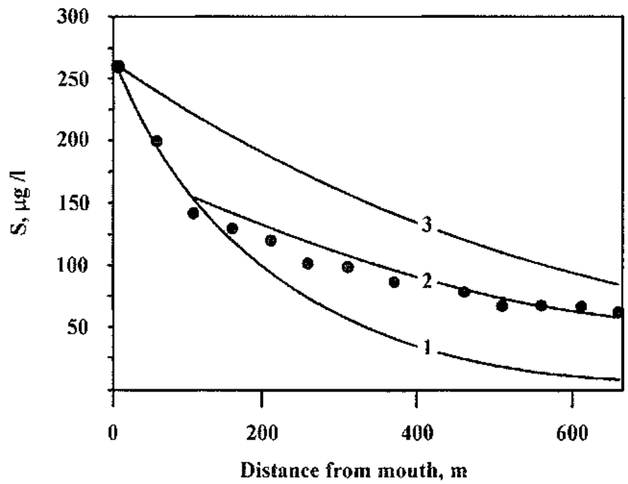

Fig. 4 Change in the suspended particulate matter concentration (S) in the river jet flow. 1: pure sedimentation process; 2: empirical data; 3: pure dilution.

CONCLUSIONS

Sedimentation processes in the Jordan River–Lake Kinneret contact zone take place inside a small area adjacent to the river mouth. Practically all the alluvium (75%) brought by the river is deposited within a short distance of the river mouth bar.

This study shows that different tracing methods can be used in parallel to provide reliable and richly informative data about alluvial sedimentation processes in a river–lake contact zone.

REFERENCES

Albarede, F. (1997) Isotopic tracers of past ocean circulation: turning lead to gold. *Science* **277** (5328), 908–909.

Andersson, P. S., Wasserburg, G. J. & Ingri, J. (1992) The sources and transport of Sr and Nd isotopes in the Baltic Sea. *Earth Planet Sci. Lett.* **113**(4), 459–472.

Berman, T. (1985) Lake Kinneret: case history of conservation in a multifunctional warm lake. In: *Proc. EWCA Congress on Lakes: Pollution and Recovery* (ed. by R. Vismara, R. Marforio, V. Meganotte & S. Cernuschi), 240–248. Andis, Rome, Italy.

Bunte, K. & Ergenzinger, P. (1989) New tracer techniques for particles in gravel bed rivers. *Bull. Soc. Geogr. Liege, Num. Spec.* **25**, 85–90.

Dahlgaard, M., Hermann, J. & Salomon, J. C. (1995) A tracer study of the transport of coastal water from the English Channel through the German Bight to the Kattegat. *J. Marine Syst.* **6**, 415–425.

Ferguson, R., Hoey, T., Watsen, S. & Werritty, A. (1996) Field evidence for rapid downstream running of river gravels through selective transport. *Geology* **24**, 179–182.

Gaspar, E. (ed.) (1987) *Modern Trends in Tracer Hydrology*. CRC Press, Boca Raton, Florida, USA.

Gophen, M. (1993) Lake Kinneret (Israel): ecosystem structure, utilization priorities and management policies. In: *Water Resources in the Middle East: Policy and Institutional Aspects* (ed. by G. E. Stout & R. A. Al-Weshah) (Proc. Int. Symp.), 184–190. International Water Resources Association, Urbana, Illinois, USA.

IAEA (1968) *Guidebook on Nuclear Techniques in Hydrology*. International Atomic Energy Agency, Vienna, Austria.

Hadas, O., Shteinman, B., Pinkas, R. & Parparov, R. (1996) Impact of the Jordan River on Lake Kinneret water quality: biological, chemical and physical factors controlling the distribution of particles at the Jordan River mouth. In: *Preservation of Our World in the Wake of Change*, vol. 6 (ed. by Y. Steinberger), 795–797. SEEQS, Jerusalem, Israel.

Hassan, M. A. (1990) Scour, fill, and burial depth of coarse material in gravel bed streams. *Earth Surf. Processes Landf.* **15**, 341–356.

Ibad-Zade, Y. (ed.) (1978) *Sediments Dynamics in Rivers and Reservoirs*. Strojizdat, Moscow, Russia (in Russian).

Ibad-Zade, Yu. A. & Shteinman, B. S. (1971) The study of sediment deposition at river mouths and bar formation (based on field measurements). In: *Proc. Fourteenth Congress IAHR*, volume 4, D15.1–D15.7. IAHR, Paris.

Kamel, A. M. & Johnson, J. W. (1963) Tracing coastal sediment by naturally radioactive minerals. In: *Proc. Fifth Conf. Coastal Engng* (Mexico City, 1962), 531–538. Council Wave Research Engineering, Richmond, USA.

Karbassi, A. R. & Shankar, R. (1994) Magnetic susceptibility of bottom sediments and suspended particulates from Mulki-Pavanje River estuary, and adjoining shelf, west coast of India. *J.Geophys. Res. Oceans* **99**(5), 207–220.

Khesin, B. & Shteinman, B. (1995) The applying of magnetic susceptibility of bottom sediments as a method for studies of sedimentation in a river–lake system. In: *Second Int. Symp. Geology Eastern Mediterranean Region*, 1–18. Jerusalem, Israel.

Kilpatrick, F. A. & Taylor, K. R. (1986) Generalization and applications of tracer dispersion data. *Wat. Res. Bull. Am. Wat. Resour. Assoc.* **22**, 537–548.

Koren, G., Gertner, I. & Shreter, U. (1982) Isotopes separation experiments in natural UF_6 by CF_4 and CO_2 lasers, analyzed by gamma-ray spectrometry. *Appl. Physics Lett.* **41**, 397.

Martin, J. M., Meybeck, M. & Heusel, M. (1970) A study on natural radioactive tracers; an application to the Gironde Estuary. *Sedimentology* **14**, 1–2.

Mikhailov, V. N. (1971) *Dynamics of the Flow and Channel at Non-tidal River Mouths* (in Russian). Hydrometeorological Press, Moscow, Russia.

Mikhailov, V. N. (1997) Methods and models for assessment of hydrological and ecological conditions of river mouth regions. In: *Proc. Monitoring Tailor-made II: Information Strategies in Water Management* (ed. by J. J. Ottens, F. A. M. Claessen, P. G. Stocks, J. G. Timmerman & R. C. Ward) (Nunspeet, The Netherlands, September 1996), 253–262. RIZA, Lelystad, The Netherlands.

Pantin, H. M. (1961) Magnetic concrete as an artificial tracer material. *NZ J. Geol. Geophys.* 4, 23–35.

Rostan, J. C., Juget, J. & Brun, A. M. (1997) Sedimentation rates measurements in former channels of the upper Rhone River using Chernobyl ^{137}Cs and ^{134}Cs as tracers. *Sci. Total Environ.* **193**, 251–262.

Schmidt, K.-H., Bley, D., Busskamp, R. & Gintz, D. (1989) Die Verwendung von Truebungsmessung, Feststofftransports im Lainbach, Oberwayern. *Gotting. Geogr. Abh.* **86**, 123–135.

Serruya, C. (ed.) (1978) *The Kinneret Monographia Biologica*. Dr Junk, The Hague, The Netherlands.

Shteinman, B. S. (1971) *Hydrology of Kura River Area* (in Russian). Hydrometeorological Press, Leningrad, USSR.

Shteinman, B. S. (1994) Sediment transport studies in river mouths with the use of natural radioactivity. In: *Proc. Seventh Int. Biannual Conf. Physics of Estuaries and Coastal Seas* (ed. by D. G. Aubrey, C. Pattiaratchi, D. Prandle & J. Dronkers), 1112–1119. Woods Hole Oceanographic Institute, Massachusetts, USA.

Shteinman, B. S., Gutman, A. & Gertner, I. (1992) The use of natural radioactivity in the sediment transport study. In: *Proc. Seventeenth Conf. Nuclear Soc. Israel* (Beer-Sheva University, Israel), 122–126. Beer-Sheva, Israel.

Shteinman, B. S. & Inbar, M. (1995) Sediment discharge of the Jordan River to Lake Kinneret. In: *Proc. Second Int. Conf. Hydro-Sci. and Engng (ICHE-95)* (ed. by Chinese Hydraulic Engineering Society International Research and Training Center on Erosion and Sedimentation), 2115–2122. Tsinghua University Press, Beiijing, China.

Shteinman, B. S. & Kamenir, Y. (1998) Decrease in suspended matter concentration with distance from the Jordan River mouth, Lake Kinneret: hydrodynamical aspects. In: *Advances in Hydro-Science and Engineering*, vol. 3. (Proc. Third International Conference on Hydro-Science and Engineering, Cottbus/Berlin, Germany), 110–124. (CD-ROM).

Shteinman, B. S., Berman, T., Inbar, M. & Gaft, M. (1998) A modified fluorescent tracer approach for studies of sediment dynamics. *Israel J. Earth Sci.* **46**, 18–31.

Yelgaonkar, V. N., Pendharkar, A. S., Navada, S. V., Pant, H. J., Mendhekar, G. N. & Rao, S. M. (1997) Investigation of bed load transport off Karwar coast, southwest coast of India. *Indian J. Marine Sci.* **26**, 91–94.