LETTER

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Activation of old carbon by erosion of coastal and subsea permafrost in Arctic Siberia

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The future trajectory of greenhouse gas concentrations depends on interactions between climate and the biogeosphere[1,2]. Thawing of Arctic permafrost could release significant amounts of carbon into the atmosphere in this century[3]. Ancient Ice Complex deposits outcropping along the ~7,000-kilometre-long coastline of the East Siberian Arctic Shelf (ESAS)[4,5], and associated shallow subsea permafrost[6,7], are two large pools of permafrost carbon[8], yet their vulnerabilities towards thawing and decomposition are largely unknown[9–11]. Recent Arctic warming is stronger than has been predicted by several degrees, and is particularly pronounced over the coastal ESAS region[12,13]. There is thus a pressing need to improve our understanding of the links between permafrost carbon and climate in this relatively inaccessible region. Here we show that extensive release of carbon from these Ice Complex deposits dominates (57 ± 2 per cent) the sedimentary carbon budget of the ESAS, the world's largest continental shelf, overwhelming the marine and topsoil terrestrial components. Inverse modelling of the dual-carbon isotope composition of organic carbon accumulating in ESAS surface sediments, using Monte Carlo simulations to account for uncertainties, suggests that 44 ± 10 teragrams of old carbon is activated annually from Ice Complex permafrost, an order of magnitude more than has been suggested by previous studies[14]. We estimate that about two-thirds (66 ± 16 per cent) of this old carbon escapes to the atmosphere as carbon dioxide, with the remainder being re-buried in shelf sediments. Thermal collapse and erosion of these carbon-rich Pleistocene coastline and seafloor deposits may accelerate with Arctic amplification of climate warming[2,13].

The large magnitude of shallow permafrost carbon pools relative to the atmospheric pools of carbon dioxide (~760 Pg) and methane (~3.5 Pg) suggests that carbon release from thawing permafrost has the potential to affect large-scale carbon cycling. Arctic permafrost can be divided into three main compartments: terrestrial (tundra and taiga) permafrost (~1,000 Pg C)[8], Ice Complex (coastal and inland) permafrost (~400 Pg C)[4,8] and subsea permafrost (~1,400 Pg C)[6,7]. Even without considering subsea permafrost, the carbon held in the top few metres of the pan-arctic permafrost constitutes approximately half of the global soil organic carbon pool[8].

Investigations of Arctic greenhouse gas releases have focused on terrestrial permafrost systems[4,9,15], and only recently on subsea permafrost[6,7,16,17], with a notable scarcity of studies on the thawing permafrost outcropping along the Arctic coast. In particular, the extensive coastline of the Eastern Siberian Sea (ESS) is dominated by exposed tall bluffs comprising ice-rich, fine-grained Ice Complex deposits (Fig. 1a). The origin of the ~1-million-km^2 deposits (with average depth 25 m) dominating northeastern Siberia (and parts of Alaska and northwestern Canada) is under some debate, but this Pleistocene material is quite distinct from peat and mineral soil of other Arctic permafrost[4,5]. These relict soils of the steppe-tundra ecosystem have high carbon contents (1–5%)[4,5]. The export of organic carbon from the eroding ESAS Ice Complex is presently estimated at 4 Tg yr^{-1} (ref. 14), yet it has also been proposed that erosion from the Lena Delta coastline alone might contribute this amount[18]. Clearly, large uncertainties remain regarding the magnitude of eroded carbon export from land to the shelf.

The extensive coastal exposure of the Ice Complex deposits (ICD) makes them potentially more vulnerable than other terrestrial permafrost; ICD retreat rates are 5–7 times higher than those of other coastal permafrost bodies[18]. A destructive thaw-erosion process brought on by thermal collapse of the coastline promotes surface

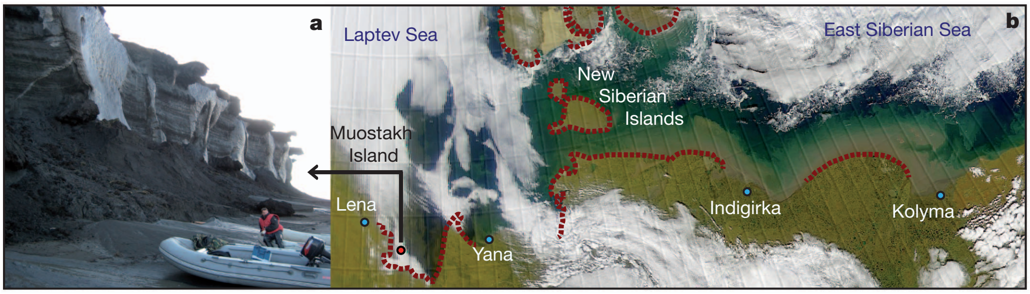

Figure 1 | Erosion of Ice Complex deposits on the East Siberian Arctic Shelf. **a**, Eroding, carbon-rich Ice Complex coast on Muostakh Island in the southeastern Laptev Sea. **b**, Erosion-induced turbidity clouds envelop several thousand kilometres of East Siberian Sea coastal waters. Note the rounded shorelines of northeastern Siberia, indicative of coastal erosion. Red dashed line shows areas of intensive ongoing erosion. (Satellite image of 24 August 2000, available at http://visibleearth.nasa.gov.)

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subsidence, with ICD loss exacerbated by the increased wave and wind erosion that accompany sea-level rise and longer ice-free seasons[2]. Satellite images show a large erosional turbidity cloud along the ESAS coastline (Fig. 1b). From limited land-based surveys, this ICD erosion is thought to be delivering as much total organic carbon to the ESAS as all its large rivers combined[19,20]. Unfortunately, these studies are limited in spatial coverage, and do not consider the fate of the released carbon in the receiving ocean. There are no field-based reports of degradation or greenhouse-gas releases of thawing ICD; however, a recent investigation of organic matter genesis in ESS surface sediments suggests that ICD erosion may dominate over planktonic and riverine sources[21]. Laboratory experiments have shown that microbial degradation begins once permafrost has thawed, implying survival of viable bacteria and an inherent lability of the very old ICD organic carbon (ICD-OC)[10,11]. In addition to terrestrial ICD, the ESAS sediments (inundated by seawater during the early Holocene epoch) also host large Pleistocene deposits, presumably containing carbon in quantities similar to those in the upper-1-m soil pool[6,8]. These reservoirs are subject to active sea-floor thermal erosion[16,17], potentially releasing as much organic carbon as coastal erosion and rivers[20]. Overall, carbon released from thawing and eroding coastal permafrost may play a quantitatively important role in the Arctic carbon cycle.

To evaluate the role of the ICD and subsea permafrost carbon (hereafter jointly referred to as ICD-PF) in the contemporary ESAS carbon cycle, we adopted an inverse approach based on deducing the contribution of this ICD-PF to carbon accumulating on the entire ESAS shelf. We analysed more than 200 sediment samples (see Methods Summary), collected during ship-based expeditions spanning the ESAS (Supplementary Fig. 2, Supplementary Methods). We used a dual-carbon-isotope ($\delta^{13}C$ and $\Delta^{14}C$) mixing model, solved with a Monte Carlo simulation strategy to account for endmember uncertainties, to deconvolve the relative contributions from ICD-PF, plankton detritus and a terrestrial/topsoil component. We then combined the fractional contribution from ICD-PF with the radiochronologically constrained sediment accumulation flux (Methods Summary and Supplementary Methods) to derive the shelf-wide re-burial flux of old carbon from permafrost.

We examined the fate of thawing ICD-OC in ambient conditions on coastal slopes of Muostakh, an island in the southeastern Laptev Sea that is disappearing as a result of erosion rates of up to 20 m yr^{-1} (refs 19,20,22; Fig. 1a). Bulk carbon contents, and molecular and isotopic compositions of ICD-OC, were assessed in conjunction with *in situ* CO_2 evasion fluxes (Supplementary Methods) to assess susceptibility of the organic carbon to degradation before delivery into coastal waters.

Radiocarbon ages of surface-sediment organic carbon ranged between 10,800 and 7,300 ^{14}C yr (Fig. 2a shows $\Delta^{14}C$ values; see also Supplementary Table 1) in the western ESS and the Dmitry Laptev Strait, regions dominated by coastal erosion (Fig. 1b). Organic-carbon radiocarbon ages were also old in the southern ESS and the Laptev Sea, ranging from 7,800 to 3,200 ^{14}C yr. Lateral shelf transport times are likely to be much smaller than these measured ^{14}C ages[23], implying significant supply of pre-aged carbon to these sediments. $\delta^{13}C$ values varied, from −28.3 to −25.2‰ near the coast, to −24.8 to −21.2‰ on the outer ESAS (Fig. 2b; Supplementary Table 1). In contrast to other world-ocean shelf seas, where the sediment organic carbon originates from planktonic and riverine sources, coastline and sediment erosion represent significant sources of organic carbon to the ESAS. The relative contribution of the three sources was deduced from their carbon isotope fingerprints. In addition to a marine source, with $\delta^{13}C = -24 \pm 3.0$‰ and $\Delta^{14}C = 60 \pm 60$‰ (mean ± standard deviation (s.d.); Supplementary Methods, Supplementary Figs 4, 5), we distinguish between two terrestrial sources: ICD-PF organic carbon (coastal, inland, and subsea; formed before inundation), with $\delta^{13}C = -26.3 \pm 0.67$‰ and $\Delta^{14}C = -940 \pm 84$‰ (Supplementary Fig. 4, Supplementary Table 4), and topsoil permafrost (topsoil-PF)

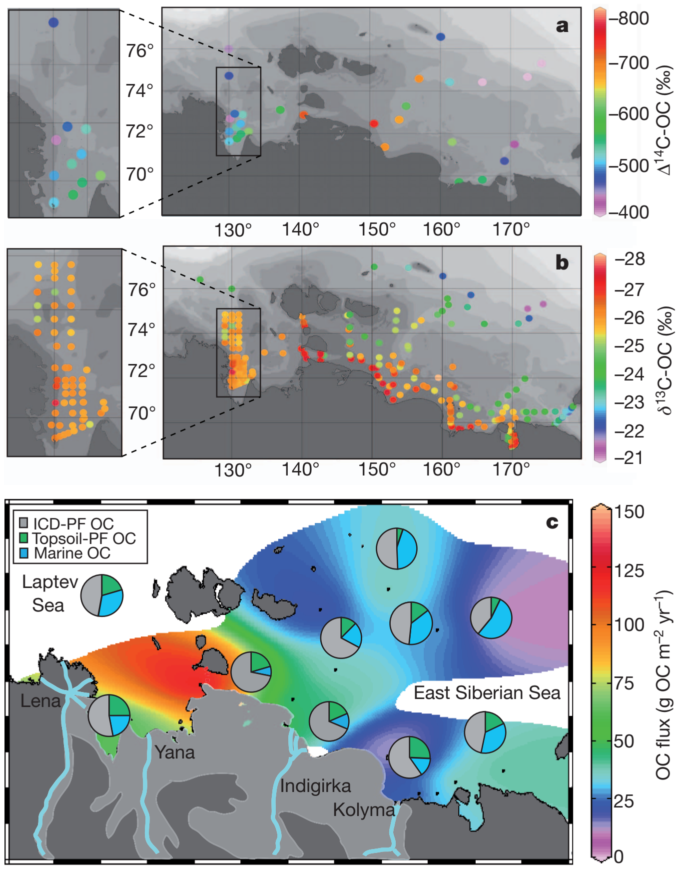

Figure 2 | Carbon isotope compositions and contribution of organic carbon sources to sediment accumulation on the East Siberian Arctic Shelf. **a**, **b**, $\Delta^{14}C$-OC (**a**) and $\delta^{13}C$-OC (**b**) signals in ESAS surface sediments. **c**, Annual sedimentary organic carbon accumulation fluxes (g OC m^{-2} yr^{-1}) and relative contributions (pie charts) of the three source pools to the surface-sediment organic carbon on the ESAS. The mean ESS contributions are: 57 ± 1.6% from ICD-PF (grey), 16 ± 3.4% from topsoil-PF (green) and 26 ± 8.0% from marine/planktonic organic carbon (blue), as identified by numerical (Monte Carlo) simulations of the dual-carbon-isotope ($\delta^{13}C$ and $\Delta^{14}C$) and endmember mixing models. Land area marked in light grey indicates the distribution of the Ice Complex[30].

organic carbon (drained from vegetation debris and the thin, surficial, annual thaw layer of the continuous permafrost regions of northeast Siberia), with $\delta^{13}C = -28.2 \pm 1.96$‰ and $\Delta^{14}C = -126 \pm 54$‰ (Supplementary Fig. 4, Supplementary Table 3 and Supplementary Methods). The endmember source assignments are based on an extensive compilation of circum-arctic literature data, yielding statistically robust and distinctive values for the three endmembers, as further explained in the Supplementary Information (Supplementary Text; Supplementary Figs 4, 5; Supplementary Tables 3, 4). Naturally, the isotopic endmember values carry uncertainties, which may be reduced in the future by additional observations of the marine and topsoil composition. The ^{13}C and ^{14}C compositions of the three endmembers are well separated from each other (Supplementary Fig. 4), which allows separation of their contributions while properly accounting for the associated uncertainties using the Monte Carlo simulation approach. We stress that the two terrestrial endmembers are solely source-based, and independent of transport or mobilization route, meaning that both ICD-PF and topsoil-PF can be delivered by coastal, delta and riverbank erosion as well as river transport. The resulting isotopic mass-balance model shows contributions of marine (planktonic) organic carbon to the shelf sediments ranging between 7% nearshore and 54% on the outer shelf, whereas topsoil-PF contributes ~30–35% close to land, decreasing to ~5% farther out (Fig. 2c).

ICD-PF constitutes 36–76% of the sedimentary organic carbon throughout the broad shelf, despite its largely coastal delivery. ICD-OC is ballasted by mineral association and rapidly settles[21,24], whereupon it is probably resuspended from the sea floor and dispersed over the shelf, mostly by bottom-boundary-layer transport[21,25,26]. Old permafrost-released erosional carbon thus dominates burial of organic carbon on the ESAS.

We estimate the net sediment burial of ICD-PF carbon using accumulation fluxes from sediment cores (36 ± 17 g OC m^{-2} yr^{-1}; all confidence intervals are 95%, unless otherwise stated; Fig. 2c, Supplementary Table 2). This was scaled up by the fraction of sea floor that is available for carbon burial (0.6), corresponding to water depth >30 m (Supplementary Fig. 2), where resuspension is negligible and sediments thus accumulate[26]. Combining the ESS shelf area (9.87×10^5 km^2) with the ICD-PF contribution to the sediment organic carbon (ESS only: 57 ± 1.6%; Supplementary Table 5) yields an overall annual ICD-PF carbon accumulation flux of 12 ± 8 TgC yr^{-1}. Inclusion of the Laptev Sea increases this value to 20 ± 8 TgC yr^{-1} (Supplementary Table 6). Hence, this approach reveals that the supply of carbon from ICD-PF erosion to the ESAS is much larger than has previously been assumed[14,19,20].

The biogeochemical composition of the eroding slopes of Muostakh Island (Fig. 3) indicates extensive organic matter degradation of the thawing ICD before delivery to the ocean. Recurring trends were observed in several properties between higher and lower elevations on the investigated slopes that are consistent with continuing degradation (Fig. 3; Supplementary Tables 7, 8), specifically: decreasing soil organic carbon content; increasing δ^{13}C of organic carbon ($\delta^{13}C_{OC}$); decreasing $\Delta^{14}C_{OC}$; decreasing ratio of high-molecular-weight *n*-alkanoic acids to high-molecular-weight *n*-alkanes; increasing ratio of even, low-molecular-weight to odd, high-molecular-weight *n*-alkanes; and increase in atmospheric CO_2 venting, deduced from field-chamber soil respiration measurements (Supplementary Methods). These trends and fluxes contrast with prior assumptions that all thawed and erosion-mobilized ICD-OC is directly flushed into the sea without sub-aerial degradation[14,19,20]. The elemental, isotopic and molecular data imply 66 ± 16% (mean ± s.d.; Supplementary Methods) down-slope degradative loss of ICD-OC.

Combining the 20 ± 8 Tg C yr^{-1} sediment re-burial flux of thawed old organic carbon with a recent estimate of water-column degradation of terrestrially derived particulate organic carbon on the ESAS of 1.4 yr^{-1} (2.5 ± 1.6 Tg C yr^{-1}; mean ± s.d.)[27] suggests an ICD-PF organic carbon flux to the marine system of 22 ± 8 Tg C yr^{-1} (Supplementary Fig. 1). Assuming an equal contribution of this flux from coastline and subsea erosion (Supplementary Table 6, which also includes 25/75% and 75/25% models), the 66 ± 16% carbon loss along the eroding coastal slopes corresponds to a carbon venting (presumably mostly CO_2) from the ICD of 22 ± 8 Tg yr^{-1} (Supplementary Fig. 1). The total remobilization of old organic carbon from thawing of ICD-PF is thus ~44 ± 10 Tg C yr^{-1} (Supplementary Table 6; Supplementary Fig. 1).

The present assessment suggests a substantially larger flux of carbon from thawing ICD permafrost (44 ± 10 Tg C yr^{-1}; Supplementary Table 6) than has been inferred previously from exclusively land-based surveys (~4 Tg C yr^{-1}; no error reported)[14]. Previous estimates of ICD erosion may have been too low for several reasons, including gross upscaling from limited point measurements of ICD retreat rates[19,20,22]. In addition, upscaling using digital shoreline length data leads to considerable underestimations[28]; and potentially large inputs from retrogressive thaw slumps and slope failure[28] are excluded when elevation change data are not included in coastline retreat measurements. Finally, bottom erosion is a previously neglected but potentially important contributor of old eroded organic carbon to the modern biogeochemical cycle on the ESAS, with erosion rates of 10–30 cm yr^{-1} (refs 18,29) at depths less than 30 m (nearly half the ESAS), where present-day bottom-water temperatures in summer are 2–3 °C and

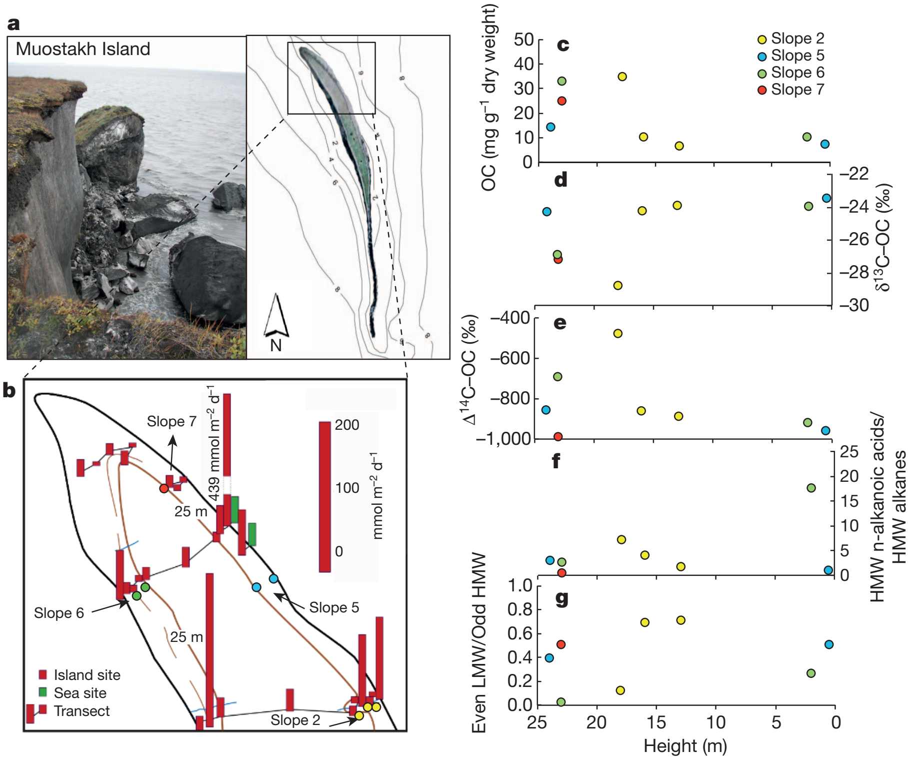

Figure 3 | Biogeochemical signals of Ice Complex organic matter degradation on Muostakh Island. **a**, Study area. **b**, Distribution of CO_2 outgassing. **c–g**, Distributions along the four studied slopes (positions indicated in **b**) of soil organic carbon content (**c**); δ^{13}C-OC signal (**d**); Δ^{14}C-OC signal (**e**); ratio of high-molecular-weight *n*-alkanoic acids to high-molecular-weight *n*-alkanes (proxy for degradation status) (**f**) and ratio of even, low-molecular-weight *n*-alkanes to odd, high-molecular-weight *n*-alkanes (proxy for bacterial biomass relative to substrate) (**g**). Ratios in **f** and **g** are molecular ratios.

have risen during the past decade[13]. Thermal collapse of the carbon-rich, permafrost-laden coastlines and sea floors may accelerate with Arctic amplification of climate warming, and could further intensify the role of old Ice Complex organic carbon in carbon cycling in the world's largest shelf sea.

METHODS SUMMARY

Surface sediments were collected on several expeditions on the ESAS in 2004, 2005, 2007 and 2008 (Supplementary Fig. 2, Supplementary Tables 1 and 9). The samples were analysed for organic carbon content and δ^{13}C (UC Davis Stable Isotope Facility, USA) and Δ^{14}C (US National Ocean Sciences Accelerator Mass Spectrometry (NOSAMS) Facility of the Woods Hole Oceanographic Institution, USA). The relative contributions of three endmember sources—Coastal Ice Complex permafrost (ICD-PF: $\delta^{13}C = -26.3 \pm 0.67$‰; $\Delta^{14}C = -940 \pm 84$‰; Supplementary Table 4); topsoil permafrost (topsoil-PF: $\delta^{13}C = -28.2 \pm 1.96$‰; $\Delta^{14}C = -126 \pm 54$‰; Supplementary Table 3); and marine organic carbon ($\delta^{13}C = -24 \pm 3.0$‰, $\Delta^{14}C = 60 \pm 60$‰; Supplementary Figs 4, 5)—to the surface sediment organic carbon content were quantified using a dual-carbon-isotope mixing model, solved with a Monte Carlo simulation approach (Supplementary Table 3). Radiochronological measurements on sediment cores from the ESAS were performed at Stockholm University and at the Radiation Research Division of the Risø National Laboratory for Sustainable Energy, Denmark (Supplementary Table 10, Supplementary Fig. 3). Total inventories of excess ^{210}Pb were used to calculate the annual sediment organic carbon accumulation on the ESAS (Supplementary Table 2). The average contribution of organic carbon from ICD-PF in the surface sediment was then used to infer the annual sediment organic carbon accumulation from ICD-PF to the ESAS.

Ice Complex samples from the slopes of Muostakh Island were collected in July 2006 (Fig. 3, Supplementary Table 7). Bulk organic carbon and δ^{13}C analyses were performed at Stockholm University (Department of Geological Sciences) and Δ^{14}C analyses at NOSAMS. The soil samples were extracted and separated for identification of molecular biomarkers using gas chromatography/mass spectrometry. In addition, soil respiration measurements were collected on Muostakh Island slopes with automatic lid chambers equipped with infrared gas analysers (Fig. 3; Supplementary Table 8). Full details of methods are available in Supplementary Methods.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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Author Contributions All authors except P.R., T.I.E. and A.A. collected samples. Preparations for bulk organic carbon analyses, stable isotope analysis and radiocarbon analyses were made by J.E.V. (sediments) and L.S.-G. (Ice Complex samples). Radiocarbon analyses on sediments were facilitated by T.I.E. L.S.-G. analysed lipid biomarkers in Muostakh Island samples. A.A. was responsible for the Monte Carlo simulations. Radiochronological measurements on sediment cores were made by P.R. and at Stockholm University. J.E.V. performed data analyses and flux calculations. J.E.V., L.S.-G. and Ö.G. wrote the paper, with input from N.S., I.P.S. and all other authors.

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PROFILE

Hungry Water: Effects of Dams and Gravel Mining on River Channels

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ABSTRACT / Rivers transport sediment from eroding uplands to depositional areas near sea level. If the continuity of sediment transport is interrupted by dams or removal of sediment from the channel by gravel mining, the flow may become sediment-starved (hungry water) and prone to erode the channel bed and banks, producing channel incision (downcutting), coarsening of bed material, and loss of spawning gravels for salmon and trout (as smaller gravels are transported without replacement from upstream). Gravel is artificially added to the River Rhine to prevent further incision and to many other rivers in attempts to restore spawning habitat. It is possible to pass incoming sediment through some small reservoirs, thereby maintaining the continuity of sediment transport through the system. Damming and mining have reduced sediment delivery from rivers to many coastal areas, leading to accelerated beach erosion. Sand and gravel are mined for construction aggregate from river channel and floodplains. In-channel mining commonly causes incision, which may propagate up- and downstream of the mine, undermining bridges, inducing channel instability, and lowering alluvial water tables. Floodplain gravel pits have the potential to become wildlife habitat upon reclamation, but may be captured by the active channel and thereby become instream pits. Management of sand and gravel in rivers must be done on a regional basis, restoring the continuity of sediment transport where possible and encouraging alternatives to river-derived aggregate sources.

As waters flow from high elevation to sea level, their potential energy is converted to other forms as they sculpt the landscape, developing complex channel networks and a variety of associated habitats. Rivers accomplish their geomorphic work using excess energy above that required to simply move water from one point on the landscape to another. In natural channels, the excess energy of rivers is dissipated in many ways: in turbulence at steps in the river profile, in the frictional resistance of cobbles and boulders, vegetation along the bank, in bends, in irregularities of the channel bed and banks, and in sediment transport (Figure 1). The transport of sand- and gravel-sized sediment is particularly important in determining channel form, and a reduction in the supply of these sediments may induce channel changes. The supply of sand and gravel may be the result of many factors, including changes in land use, vegetation, climate, and tectonic activity. This paper is concerned specifically with the response of river channels to a reduction in the supply of these sediments by dams and gravel mining.

Sediment is transported mostly as suspended load: clay, silt, and sand held aloft in the water column by turbulence, in contrast to bedload: sand, gravel, cobbles, and boulders transported by rolling, sliding, and bouncing along the bed (Leopold and others 1964). Bedload ranges from a few percent of total load in lowland rivers to perhaps 15% in mountain rivers (Collins and Dunne 1990), to over 60% in some arid catchments (Schick and Lekach 1993). Although a relatively small part of the total sediment load, the arrangement of bedload sediments constitutes the architecture of sand- and gravel-bed channels. Moreover, gravel and cobbles have tremendous ecological importance, as habitat for benthic macroinvertebrates and as spawning habitat for salmon and trout (Kondolf and Wolman 1993).

The rate of sediment transport typically increases as a power function of flow; that is, a doubling of flow typically produces more than a doubling in sediment transport (Richards 1982), and most sediment transport occurs during floods.

KEY WORDS: Dams; Aquatic habitat; Sediment transport; Erosion; Sedimentation; Gravel mining

Continuity of Sediment Transport in River Systems

Viewed over a long term, runoff erodes the land surface, and the river network carries the erosional products from each basin. The rates of denudation, or lowering of the land by erosion, range widely. The Appalachian Mountains of North America are being denuded about 0.01 mm/yr (Leopold and others 1964), the central Sierra Nevada of California about 0.1

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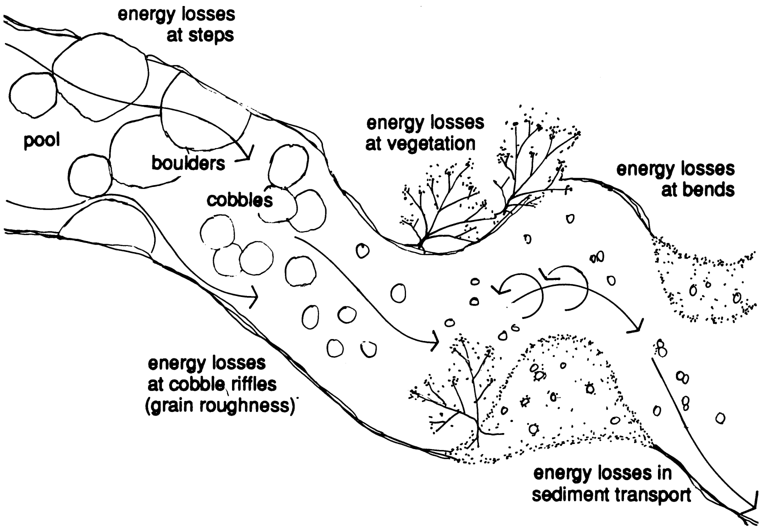

Figure 1. Diagram of energy dissipation in river channels.

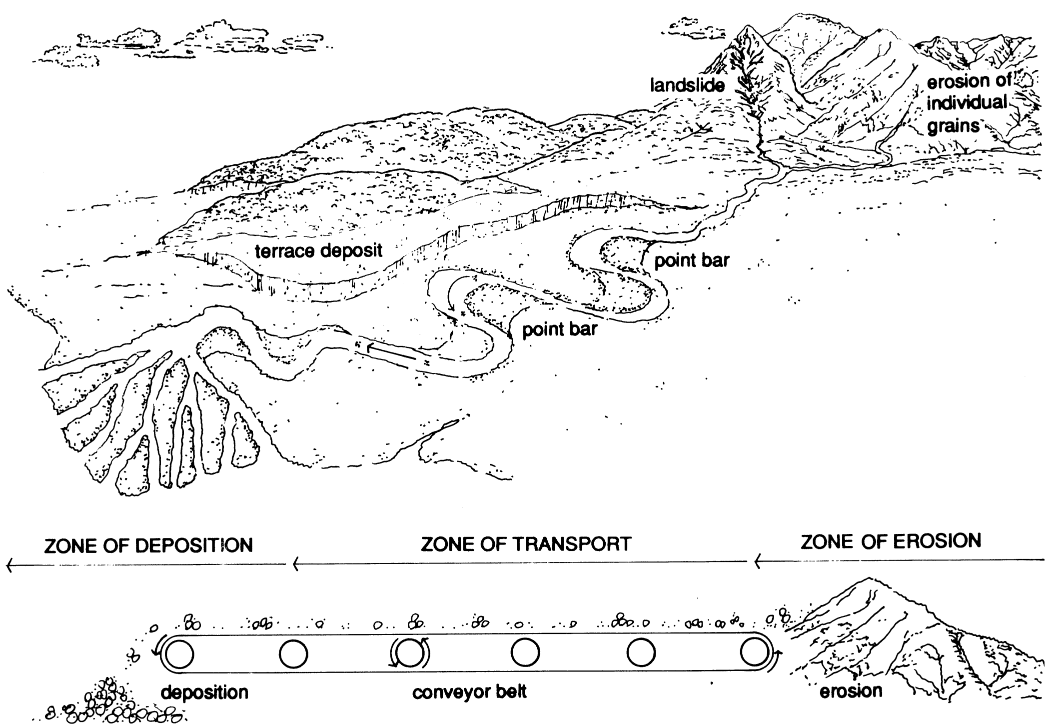

Figure 2. Zones of erosion, transport, and deposition, and the river channel as conveyor belt for sediment. (Reprinted from Kondolf 1994, with kind permission of Elsevier Science-NL.)

mm/yr (Kondolf and Matthews 1993), the Southern Alps of New Zealand about 11 mm/yr (Griffiths and McSaveney 1983), and the southern Central Range of Taiwan over 20 mm/yr (Hwang 1994). The idealized watershed can be divided into three zones: that of erosion or sediment production (steep, rapidly eroding headwaters), transport (through which sediment is moved more or less without net gain or loss), and deposition (Schumm 1977) (Figure 2). The river channel in the transport reach can be viewed as a conveyor belt, which transports the erosional products downstream to the ultimate depositional sites below sea level. The size of sediment typically changes along the length of the river system from gravel, cobbles, and boulders in steep upper reaches to sands and silts in low-gradient downstream reaches, reflecting diminution in size by weathering and abrasion, as well as sorting of sizes by flowing water.

Transport of sediment through the catchment and along the length of the river system is continuous. Increased erosion in the upper reaches of the catchment can affect the river environment many miles downstream (and for years or decades) as the increased sediment loads propagate downstream through the river network. On Redwood Creek in Redwood National Park, California, the world's tallest trees are threatened with bank erosion caused by channel aggradation (building up of sediment in the channel), which in turn was caused by clear-cutting of timber on steep slopes in the upper part of the catchment (Madej and Ozaki 1996, Janda 1978).

Along the river channel conveyor belt, channel forms (such as gravel bars) may appear stable, but the grains of which they are composed may be replaced annually or biannually by new sediment from upstream. Similarly, the sediments that make up the river floodplain (the valley flat adjacent to the channel) are typically mobile on a time scale of decades or centuries. The floodplain acts as a storage reservoir for sediments transported in the channel, alternately storing sediments by deposition and releasing sediment to the channel by bank erosion. For example, the Carmel River, California, is flanked by flat surfaces (terraces) that step up from the river. The lowest terrace is the channel of sand and gravel deposited by the 1911 flood, but the surface now stands about 4 m above the present, incised channel (Kondolf and Curry 1986). By 1960, the terrace had been subdivided for low-density housing, despite the recent origin of the land and the potential for future shifts in channel position.

A river channel and floodplain are dynamic features that constitute a single hydrologic and geomorphic unit characterized by frequent transfers of water and sediment between the two components. The failure to appreciate the integral connection between floodplain and channel underlies many environmental problems in river management today.

Effects of Dams

Dams and diversions are constructed and operated for a wide variety of purposes including residential, commercial, and agricultural water supply; flood and / or debris control; and hydropower production. Regardless of their purpose, all dams trap sediment to some degree and most alter the flood peaks and seasonal distribution of flows, thereby profoundly changing the character and functioning of rivers. By changing flow regime and sediment load, dams can produce adjustments in alluvial channels, the nature of which depends upon the characteristics of the original and altered flow regimes and sediment loads.

Dams disrupt the longitudinal continuity of the river system and interrupt the action of the conveyor belt of sediment transport. Upstream of the dam, all bedload sediment and all or part of the suspended load (depending upon the reservoir capacity relative to inflow) (Brune 1953) is deposited in the quiet water of the reservoir (reducing reservoir capacity) and upstream of the reservoir in reaches influenced by backwater. Downstream, water released from the dam possesses the energy to move sediment, but has little or no sediment load. This clear water released from the dam is often referred to as hungry water, because the excess energy is typically expended on erosion of the channel bed and banks for some years following dam construction, resulting in incision (downcutting of the bed) and coarsening of the bed material until equilibrium is reached and the material cannot be moved by the flows. Reservoirs also may reduce flood peaks downstream, potentially reducing the effects of hungry water, inducing channel shrinking, or allowing fine sediments to accumulate in the bed.

Channel Incision

Incision below dams is most pronounced in rivers with fine-grained bed materials and where impacts on flood peaks are relatively minor (Williams and Wolman 1984). The magnitude of incision depends upon the reservoir operation, channel characteristics, bed material size, and the sequence of flood events following dam closure. For example, the easily eroded sand bed channel of the Colorado River below Davis Dam, Arizona, has incised up to 6 m, despite substantial reductions in peak flows (Williams and Wolman 1984). In contrast, the Mokelumne River below Camanche Dam in California has experienced such a dramatic reduction in flood regime (and consequent reduction in sediment transport capacity) that no incision has been documented and gravels are reported to have become compacted and immobile (FERC 1993).

Reduction in bedload sediment supply can induce a change in channel pattern, as occurred on Stony Creek, a tributary to the Sacramento River 200 km north of San Francisco. Since the closure of Black Butte Dam in 1963, the formerly braided channel has adopted a single-thread meandering pattern, incised, and migrated laterally, eroding enough bedload sediment to compensate for about 20% of the bedload now trapped by Black Butte Dam on an annual average basis (Kondolf and Swanson 1993).

Bed Coarsening and Loss of Spawning Gravels

Channel erosion below dams is frequently accompanied by a change in particle size on the bed, as gravels and finer materials are winnowed from the bed and transported downstream, leaving an armor layer, a coarse lag deposit of large gravel, cobbles, or boulders. Development of an armor layer is an adjustment by the river to changed conditions because the larger particles are less easily mobilized by the hungry water flows below the dam. The armor layer may continue to coarsen until the material is no longer capable of being moved by the reservoir releases or spills, thereby limiting the ultimate depth of incision (Williams and Wolman 1984, Dietrich and others 1989).

The increase in particle size can threaten the success of spawning by salmonids (salmon and trout), which use freshwater gravels to incubate their eggs. The female uses abrupt upward jerks of her tail to excavate a small pit in the gravel bed, in which she deposits her eggs and the male releases his milt. The female then loosens gravels from the bed upstream to cover the eggs and fill the pit. The completed nests (redds) constitute incubation environments with intragravel flow of water past the eggs and relative protection from predation. The size of gravel that can be moved to create a redd depends on the size of the fish, ranging in median diameter from about 15 mm for small trout to about 50 mm for large salmon (Kondolf and Wolman 1993).

Below dams, the bed may coarsen to such an extent that the fish can no longer move the gravel. The Upper Sacramento River, California, was once the site of extensive spawning by chinook salmon (*Oncorhynchus tshawytscha*), but massive extraction of gravel from the riverbed, combined with trapping of bedload sediment behind Shasta Dam upstream and release of hungry water, has resulted in coarsening of the bed such that spawning habitat has been virtually eliminated in the reach (Figure 3) (Parfitt and Buer 1980). The availability of spawning gravels can also be reduced by incision below dams when formerly submerged gravel beds are isolated as terrace or floodplain deposits. Encroaching vegetation can also stabilize banks and further reduce gravel recruitment for redds (Hazel and others 1976).

Figure 3. Keswick Dam and the channel of the Sacramento River downstream. (Photograph by the author, January 1989.)

Gravel Replenishment Below Dams

Gravels were being artificially added to enhance available spawning gravel supply below dams on at least 13 rivers in California as of 1992 (Kondolf and Matthews 1993). The largest of these efforts is on the Upper Sacramento River, where from 1979 to 2000 over US$22 million will have been spent importing gravel (derived mostly from gravel mines on tributaries) into the river channel (Denton 1991) (Figure 4). While these projects can provide short-term habitat, the amount of gravel added is but a small fraction of the bedload deficit below Shasta Dam, and gravels placed in the main river have washed out during high flows, requiring continued addition of more imported gravel (California Department of Water Resources 1995). On the Merced, Tuolumne, and Stanislaus rivers in California, a total of ten sites were excavated and back-filled with smaller gravel to create spawning habitat for chinook salmon from 1990 to 1994. However, the gravel sizes imported were mobile at high flows that could be expected to occur every 1.5–4.0 years, and subsequent channel surveys have demonstrated that imported gravels have washed out (Kondolf and others 1996a,b).

On the border between France and Germany, a series of hydroelectric dams was constructed on the River Rhine (progressing downstream) after 1950, the last of which (the Barrage Iffezheim) was completed in the 1970s. To address the sediment deficit problem downstream of Iffezheim, an annual average of 170,000 tonnes of gravel (the exact amount depending on the

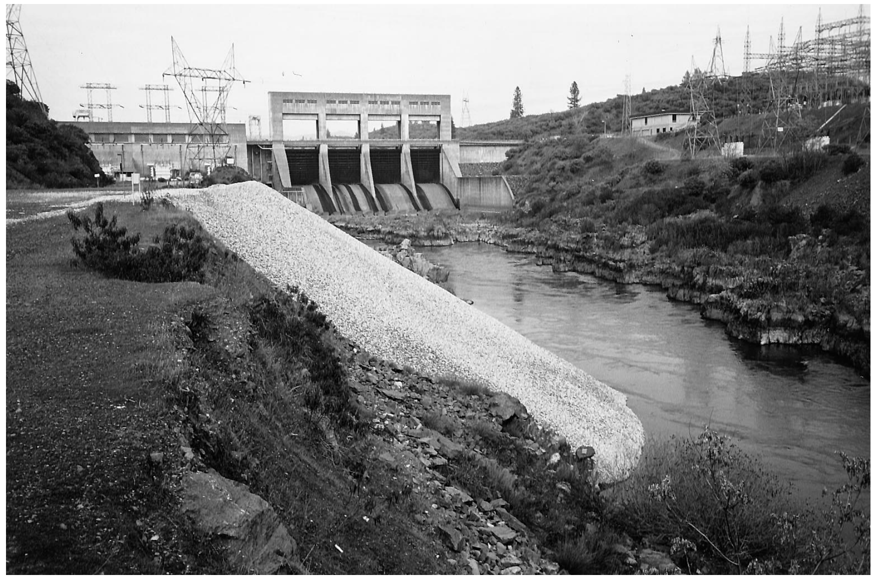

Figure 4. Gravel replenishment to the Sacramento River below Keswick Dam. (Photograph by the author, January 1991.)

magnitude of the year's runoff) are added to the river (Figure 5). This approach has proved successful in preventing further incision of the riverbed downstream (Kuhl 1992). It is worth noting that the quantity of gravel added each year is not equivalent to the unregulated sediment load of the Rhine; the river's capacity to transport sediment has also been reduced because the peak discharges have been reduced by reservoir regulation. The amount of sediment added satisfies the transport capacity of the existing channel, which has been highly altered for navigation and hydroelectric generation.

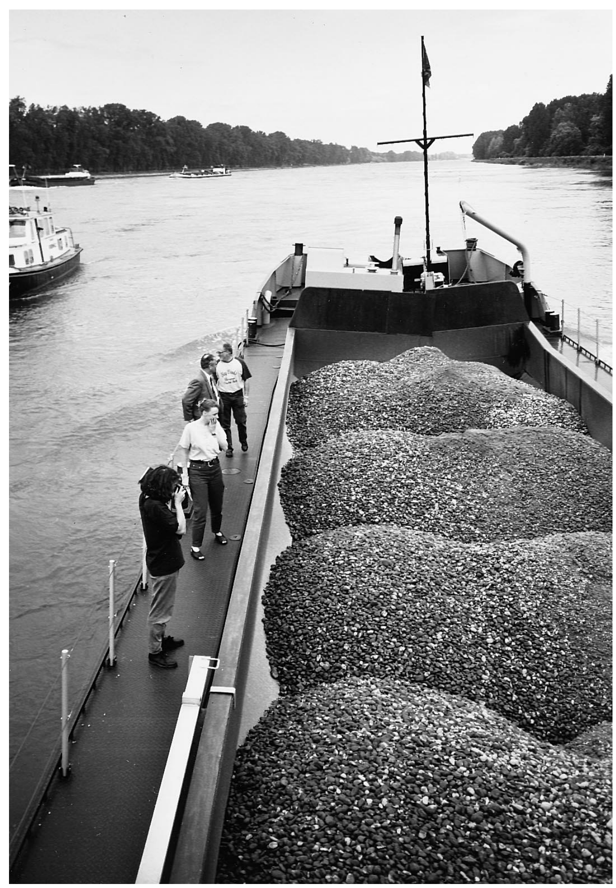

Figure 5. Barge artificially feeding gravel into the River Rhine downstream of the Barrage Iffezheim. (Photograph by author, June 1994.)

Sediment Sluicing and Pass-Through from Reservoirs

The downstream consequences of interrupting the flux of sand and gravel transport would argue for designing systems to pass sediment through reservoirs (and thereby reestablish the continuity of sediment transport). To date, most such efforts have been undertaken to solve problems with reservoir sedimentation, particularly deposits of sediment at tunnel intakes and outlet structures, rather than to solve bedload sediment supply problems downstream. These efforts have been most common in regions with high sediment yields such as Asia (e.g., Sen and Srivastava 1995, Chongshan and others 1995, Hassanzadeh 1995). Small diversion dams (such as those used to divert water in run-of-the-river hydroelectric generating projects) in steep V-shaped canyons have the greatest potential to pass sediment. Because of their small size, these reservoirs (or forebays) can easily be drawn down so that the river's gradient and velocity are maintained through the dam

Figure 6. Sand deposited in the bed of the Kern River as a result of sluicing from Democrat Dam in 1986. (Photograph by the author, December 1990.)

at high flow. Large-capacity, low-level outlets are required to pass the incoming flow and sediment load.

If low-level outlets are open at high flow and the reservoir is drawn down, a small reservoir behaves essentially as a reach of river, passing inflowing sediment through the dam outlets. In such a sediment pass-through approach, the sediment is delivered to downstream reaches in essentially the same concentration and seasonal flood flows as prevailed in the predam regime. This approach was employed at the old Aswan Dam on the River Nile and on the Bhatgurk Reservoir on the Yeluard River in India (Stevens 1936). Similarly, on the River Inn in Austria and Germany, floodwaters with high suspended loads are passed through a series of hydropower reservoirs in a channel along the reservoir bottom confined by training walls (Hack 1986, Westrich and others 1992). If topographic conditions are suitable, sediment-laden floodwater may be routed around a reservoir in a diversion tunnel or permitted to pass through the length of the reservoir as a density current vented through a bottom sluice on the dam (Morris 1993). The Nan-Hwa Reservoir in Taiwan was designed with a smaller upstream forebay from which sediment is flushed into a diversion tunnel, allowing only relatively clear water to pass into the main reservoir downstream (Morris 1993).

If sediment is permitted to accumulate in the reservoir and subsequently discharged as a pulse (sediment sluicing), the abrupt increase in sediment load may alter substrate and aquatic habitat conditions downstream of the dam. The most severe effects are likely to occur when sediment accumulated over the flood season is discharged during baseflow (by opening the outlet pipe or sluice gates and permitting the reservoir to draw down sufficiently to resuspend sediment and move bedload), when the river's transporting capacity is inadequate to move the increased load. On the Kern River, the Southern California Edison Company (an electric utility) obtained agency permission to sluice sand from Democrat Dam in 1986, anticipating that the sand would be washed from the channel the subsequent winter. However, several years of drought ensued, and the sand remained within the channel until high flows in 1992 (Figure 6) (Dan Christenson, California Department of Fish and Game, Kernville, personal communication 1992).

On those dams larger than small diversion structures, the sediment accumulated around the outlet is usually silt and clay, which can be deleterious to aquatic habitat and water quality (Bjornn and Reiser 1991). Opening of the low-level outlet on Los Padres Dam on the Carmel River, California, released silt and clay, which resulted in a large fish kill in 1980 (Buel 1980). The dam operator has since been required to use a suction dredge to maintain the outlet (D. Dettman, Monterey Peninsula Water Management District, personal communication 1990). On the Dan River in Danville, Virginia, toxicity testing is required during sluicing of fine sediments from Schoolfield Dam (FERC 1995). Accidental sluices have also occurred during maintenance or repair work, sometimes resulting in substantial cleanup operations for the dam operators (Ramey and Beck 1990, Kondolf 1995).

Less serious effects are likely when the sediment pulse is released during high flows, which will have elevated suspended loads, but which can typically disperse the sediment for some distance downstream. The Jansanpei Reservoir in Taiwan is operated to provide power for the Taiwan Sugar Company, which needs power for processing only from November to April. The reservoir is left empty with open low-level outlets for the first two months of the rainy season (May and June), so sediments accumulated over the months of July–April can be flushed by the first high flows of the season before storing water in the latter part of the rainy season (Hwang 1994).

At present, sediment pass-through is not commonly done in North America, probably because of the limited capacity of many low-level outlets and because of concern that debris may become stuck in the outlets, making them impossible to close later, and making diversions impossible during the rest of the wet season until flows drop sufficiently to fix the outlets. These concerns can probably be addressed with engineering solutions, such as trash racks upstream of the outlet and redundancies in gate structures on the low-level outlet. Large reservoirs cannot be drawn down sufficiently to transport sediment through their length to the outlet works, for such a drawdown would eliminate carryover storage from year to year, an important benefit from large reservoirs.

In most reservoirs in the United States, sediment is simply permitted to accumulate. Active management of sediment in reservoirs has been rare, largely because the long-term costs of reservoir storage lost to sedimentation have not been incorporated into decision-making and planning for reservoirs. Most good reservoir sites are already occupied by reservoirs, and where suitable replacement reservoir sites exist, the current cost of replacement storage (about US\$3/m^3 in California) is considerably higher than original storage costs. Mechanical removal is prohibitively expensive in all but small reservoirs, with costs of \$15–\$50/m^3 cited for the Feather River in California (Kondolf 1995).

Channel Narrowing and Fine Sediment Accumulation Below Dams

While many reservoirs reduce flood peaks, the degree of reduction varies considerably depending upon reservoir size and operation. The larger the reservoir capacity relative to river flow and the greater the flood pool available during a given flood, the greater the reduction in peak floods. Flood control reservoirs typically contain larger floods than reservoirs operated solely for water supply. Downstream of the reservoir, encroachment of riparian vegetation into parts of the active channel may occur in response to a reduction in annual flood scour and sediment deposition (Williams and Wolman 1984). Channel narrowing has been greatest below reservoirs that are large enough to contain the river's largest floods. In some cases, fine sediment delivered to the river channel by tributaries accumulates in spawning gravels because the reservoir-reduced floods are inadequate to flush the riverbed clean.

On the Trinity River, California, construction of Trinity Dam in 1960 reduced the two-year flow from 450 m^3/sec to 9 m^3/sec. As a result of this dramatic change in flood regime, encroachment of vegetation and deposition of sediment has narrowed the channel to 20%–60% of its predam width (Wilcock and others 1996). Accumulation of tributary-derived decomposed granitic sand in the bed of the Trinity River has led to a decline of invertebrate and salmonid spawning habitat (Fredericksen, Kamine and Associates 1980). Experimental, controlled releases were made in 1991, 1992, 1993, 1995, and 1996 to determine the flows required to flush the sand from the gravels (Wilcock and others 1996).

Such flushing flows increasingly have been proposed for reaches downstream of reservoirs to remove fine sediments accumulated on the bed and to scour the bed frequently enough to prevent encroachment of riparian vegetation and narrowing of the active channel (Reiser and others 1989). The objectives of flushing flows have not always been clearly specified, nor have potential conflicts always been recognized. For example, a discharge that mobilizes the channel bed to flush interstitial fine sediment will often produce comparable transport rates of sand and gravel, eliminating the selective transport of sand needed to reduce the fine sediment content in the bed, and resulting in a net loss of gravel from the reach given its lack of supply from upstream (Kondolf and Wilcock 1996).

Coastal Erosion

Beaches serve to dissipate wave action and protect coastal cliffs. Sand may be supplied to beaches from headland erosion, river transport, and offshore sources. If sand supply is reduced through a reduction in sediment delivery from rivers and streams, the beach may become undernourished, shrink, and cliff erosion may be accelerated. This process by which beaches are reduced or maintained can be thought of in terms of a sediment balance between sources of sediment (rivers and headland erosion), the rate of longshore transport along the coast, and sediment sinks (such as loss to deeper water offshore) (Inman 1976). Along the coast of southern California, discrete coastal cells can be identified, each with distinct sediment sources (sediment delivery from river mouths) and sinks (losses to submarine canyons). For example, for the Oceanside littoral cell, the contribution from sediment sources (Santa Margarita, San Luis Rey, and San Dieguito rivers and San Mateo and San Juan creeks) was estimated,

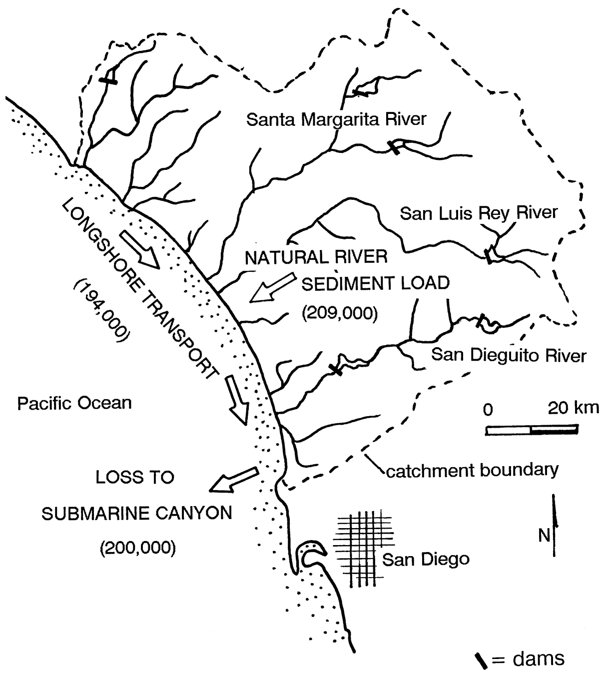

Figure 7. The Oceanside littoral cell, showing estimated sand and gravel supply from rivers, longshore transport, and loss to the La Jolla submarine canyon (in m^3/yr). (Adapted from Inman 1985, used by permission.)

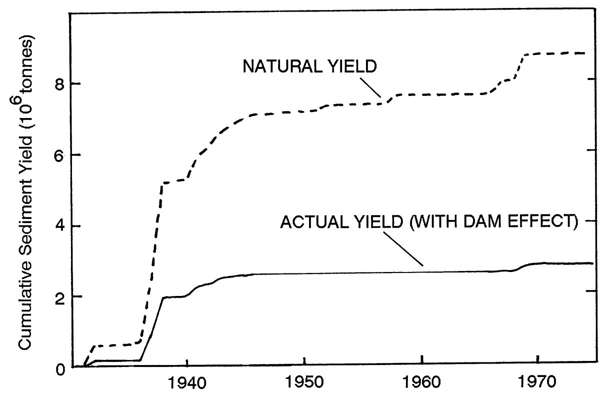

Figure 8. Cumulative reduction in suspended sediment supply from the catchment of the San Luis Rey River due to construction of Henshaw Dam. (Adapted from Brownlie and Taylor 1981.)

under natural conditions, at 209,000 m^3/yr, roughly balancing the longshore transport rate of 194,000 m^3/yr and the loss into the La Jolla submarine canyon of 200,000 m^3/yr (Figure 7) (Inman 1985).

The supply of sediment to beaches from rivers can be reduced by dams because dams trap sediment and because large dams typically reduce the magnitude of floods, which transport the majority of sediment (Jenkins and others 1988). In southern California rivers, most sediment transport occurs during infrequent floods (Brownlie and Taylor 1981), but it is these energetic events that flood control dams are constructed to prevent. On the San Luis Rey River, one of the principal sources of sediment for the Oceanside littoral cell, Henshaw Dam reduced suspended sediment yield by 6 million tonnes (Figure 8), total sand and gravel yield by 2 million tonnes (Brownlie and Taylor 1981).

Ironically, by trapping sediment and reducing peak flows, the flood control dams meant to reduce property damage along rivers contribute to property damage along the coast by eliminating sediment supply to the protective beaches. For the rivers contributing sediment to the Oceanside littoral cell as a whole, sediment from about 40% of the catchment area is now cut off by dams. Because the rate of longshore transport (a function of wave energy striking the coast) is unchanged, the result has been a sediment deficit, loss of beach sand, and accelerated coastal erosion (Inman 1985).

The effects of sediment trapping by dams has been exacerbated in combination with other effects such as channelization and instream sand and gravel mining (discussed below). Although sluicing sediment from reservoirs has been considered in the Los Angeles Basin, passing sediment through urban flood control channels could cause a number of problems, including decreasing channel capacity (Potter 1985). "Beach nourishment" with imported sediment dredged from reservoirs and harbors has been implemented along many beaches in southern California (Inman 1976, Allayaud 1985, Everts 1985). In some cases, sand is transported to critical locations on the coast via truck or slurry pipelines. The high costs of transportation, sorting for the proper size fractions, and cleaning contaminated dredged material, as well as the difficulty in securing a stable supply of material make these options infeasible in some places (Inman 1976).

To integrate considerations of fluvial sediment supply in the maintenance of coastal beaches into the existing legal framework, a system of "sand rights," analogous to water rights, has been proposed (Stone and Kaufman 1985).

Gravel Mining in River Systems

Sand and gravel are used as construction aggregate for roads and highways (base material and asphalt), pipelines (bedding), septic systems (drain rock in leach fields), and concrete (aggregate mix) for highways and buildings. In many areas, aggregate is derived primarily from alluvial deposits, either from pits in river floodplains and terrances, or by in-channel (instream) mining, removing sand and gravel directly from river beds with heavy equipment.

Sand and gravel that have been subject to prolonged transport in water (such as active channel deposits) are particularly desirable sources of aggregate because weak materials are eliminated by abrasion and attrition, leaving durable, rounded, well-sorted gravels (Barksdale 1991). Instream gravels thus require less processing than many other sources, and suitable channel deposits are commonly located near the markets for the product or on transportation routes, reducing transportation costs (which are the largest costs in the industry). Moreover, instream gravels are typically of sufficiently high quality to be classified as ''PCC-grade'' aggregate, suitable for use in production of Portland Cement concrete (Barksdale 1991).

Effects of Instream Gravel Mining

Instream mining directly alters the channel geometry and bed elevation and may involve extensive clearing, diversion of flow, stockpiling of sediment, and excavation of deep pits (Sandecki 1989). Instream mining may be carried out by excavating trenches or pits in the gravel bed, or by gravel bar skimming (or scalping), removing all the material in a gravel bar above an imaginary line sloping upwards from the summer water's edge. In both cases, the preexisting channel morphology is disrupted and a local sediment deficit is produced, but trenching also leaves a headcut on its upstream end. In addition to the direct alterations of the river environment, instream gravel mining may induce channel incision, bed coarsening, and lateral channel instability (Kondolf 1994).

Channel Incision and Bed Coarsening

By removing sediment from the channel, instream gravel mining disrupts the preexisting balance between sediment supply and transporting capacity, typically inducing incision upstream and downstream of the extraction site. Excavation of pits in the active channel alters the equilibrium profile of the streambed, creating a locally steeper gradient upon entering the pit (Figure 9). This over-steepened nickpoint (with its increased stream power) commonly erodes upstream in a process known as headcutting. Mining-induced incision may propagate upstream for kilometers on the main river (Scott 1973, Stevens and others 1990) and up tributaries (Harvey and Schumm 1987). Gravel pits trap much of the incoming bedload sediment, passing hungry water downstream, which typically erodes the channel bed and banks to regain at least part of its sediment load (Figure 9).

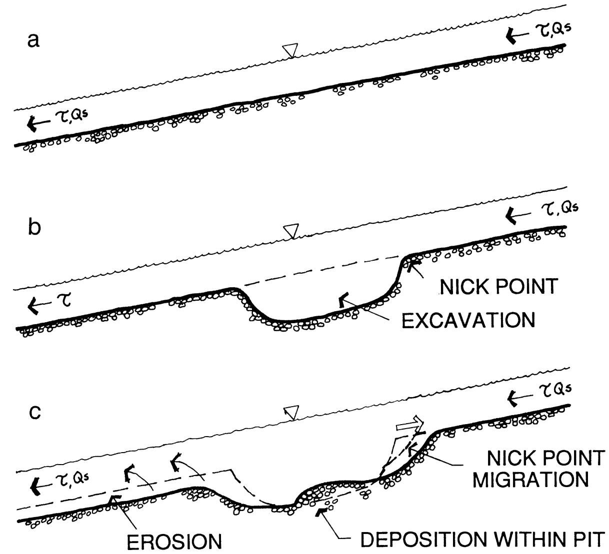

Figure 9. Incision produced by instream gravel mining. **a:** The initial, preextraction condition, in which the river's sediment load (Q_s) and the shear stress (τ) available to transport sediment are continuous through the reach. **b:** The excavation creates a nickpoint on its upstream end and traps sediment, interrupting the transport of sediment through the reach. Downstream, the river still has the capacity to transport sediment (τ) but no sediment load. **c:** The nickpoint migrates upstream, and hungry water erodes the bed downstream, causing incision upstream and downstream. (Reprinted from Kondolf 1994, with kind permission of Elsevier Science-NL.)

A vivid example of mining-induced nickpoint migration appears on a detailed topographic map prepared from analysis of 1992 aerial photographs of Cache Creek, California. The bed had been actively mined up to the miner's property boundary about 1400 m downstream of Capay Bridge, with a 4-m high headwall on the upstream edge of the excavation. After the 1992 winter flows, a nickpoint over 3 m deep extended 700 m upstream from the upstream edge of the pit (Figure 10). After the flows of 1993, the nickpoint had migrated another 260 m upstream of the excavation (not shown), and in the 50-yr flood of 1995, the nickpoint migrated under the Capay Bridge, contributing to the near-failure of the structure (Northwest Hydraulics Consultants 1995).

On the Russian River near Healdsburg, California, instream pit mining in the 1950s and 1960s caused channel incision in excess of 3–6 m over an 11-km length of river (Figure 11). The formerly wide channel of the Russian River is now incised, straighter, prevented from migrating across the valley floor by levees, and thus unable to maintain the diversity of successional

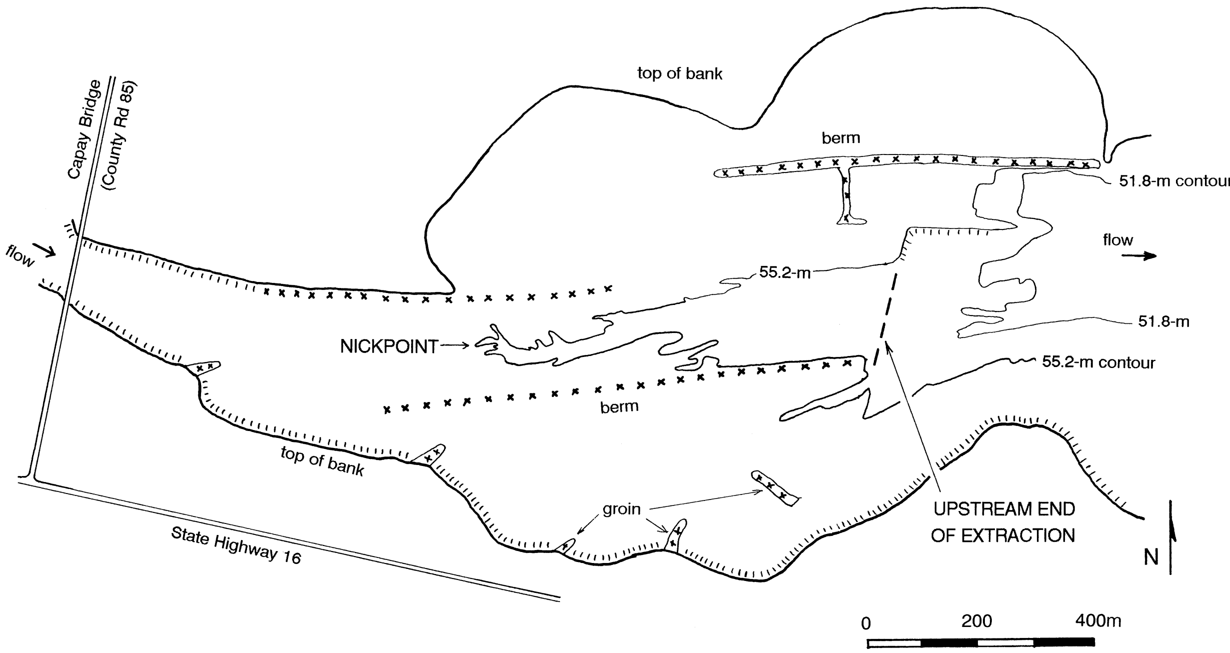

Figure 10. Nickpoint upstream of 4-m-deep gravel pit in the bed of Cache Creek, California, as appearing on a topographic map of Cache Creek prepared from fall 1992 aerial photographs. Original map scale 1:2400, contour interval 0.6 m.

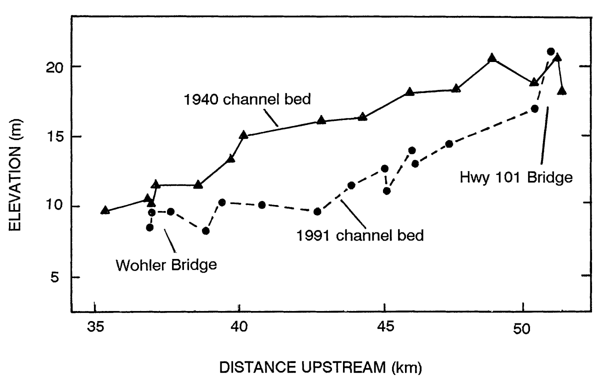

Figure 11. Longitudinal profile of the Russian River, near Healdsburg, California, showing incision from 1940 to 1991. (Redrawn from Florsheim and Goodwin 1993, used by permission.)

stages of vegetation associated with an actively migrating river (Florsheim and Goodwin 1993). With continued extraction, the bed may degrade down to bedrock or older substrates under the recent alluvium (Figure 12). Just as below dams, gravel-bed rivers may become armored, limiting further incision (Dietrich and others 1989), but eliminating salmonid spawning habitat.

In many rivers, gravel mining has been conducted downstream of dams, combining the effects of both impacts to produce an even larger sediment deficit. On the San Luis Rey River downstream of Henshaw Dam, five gravel mining operations within 8 km of the Highway 395 bridge extract a permitted volume of approximately 300,000 m^3/yr, about 50 times greater than the estimated postdam bedload sediment yield (Kondolf and Larson 1995), further exacerbating the coastal sediment deficit.

Incision of the riverbed typically causes the alluvial aquifer to drain to a lower level, resulting in a loss of aquifer storage, as documented along the Russian River (Sonoma County 1992). The Lake County (California) Planning Department (Lake County 1992) estimated that incision from instream mining in small river valleys could reduce alluvial aquifer storage from 1% to 16%, depending on local geology and aquifer geometry.

Undermining of Structures

The direct effects of incision include undermining of bridge piers and other structures, and exposure of buried pipeline crossings and water-supply facilities. Headcutting of over 7 m from an instream gravel mine downstream on the Kaoping River, Taiwan, threatens the Kaoping Bridge, whose downstream margin is now protected with gabions, massive coastal concrete jacks, and lengthened piers (Figure 13).

On the San Luis Rey River, instream gravel mining has not only reduced the supply of sediment to the coast, but mining-induced incision has exposed aqueducts, gas pipelines, and other utilities buried in the

Figure 12. Tributary to the Sacramento River near Redding, California, eroded to bedrock as a result of instream mining. (Photograph by author, January 1989.)

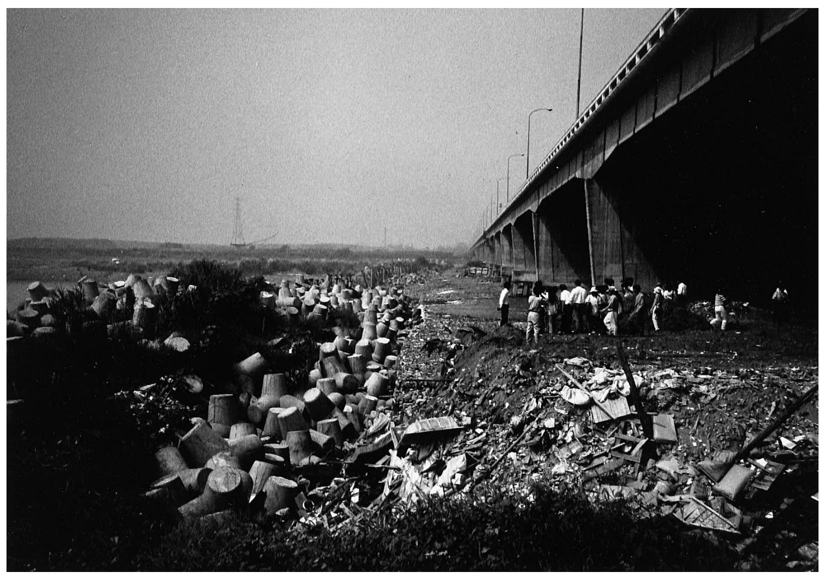

Figure 13. Undercutting and grade control efforts along the downstream side of the Kaoping Bridge over the Kaoping River, Taiwan, to control incision caused by massive gravel mining downstream. (Photograph by the author, October 1995.)

bed and exposed the footings of a major highway bridge (Parsons Brinkeroff Gore & Storrie, Inc. 1994). The Highway 32 bridge over Stony Creek, California, has been undermined as a result of intensive gravel mining directly upstream and downstream of the bridge (Kondolf and Swanson 1993). Municipal water supply intakes have been damaged or made less effective on the Mad (Lehre and others 1993) and Russian (Marcus 1992) rivers in California as the layer of overlying gravel has decreased due to incision.

Channel Instability

Instream mining can cause channel instability through disruption of the existing equilibrium channel form or undercutting of banks caused by incision. Gravel mining in Blackwood Creek, California, caused incision and channel instability upstream and downstream, increasing the stream's sediment yield fourfold (Todd 1989). As a nickpoint migrates upstream, its incision and bank undercutting release additional sediment to downstream reaches, where the channel may aggrade and thereby become unstable (Sear and Archer 1995). Incision in the mainstem Russian River propagated up its tributary Dry Creek, resulting in undercutting of banks, channel widening (from 10 to 400 m in places), and destabilization, increasing delivery of sand and gravel to the mainstem Russian River (Harvey and Schumm 1987).

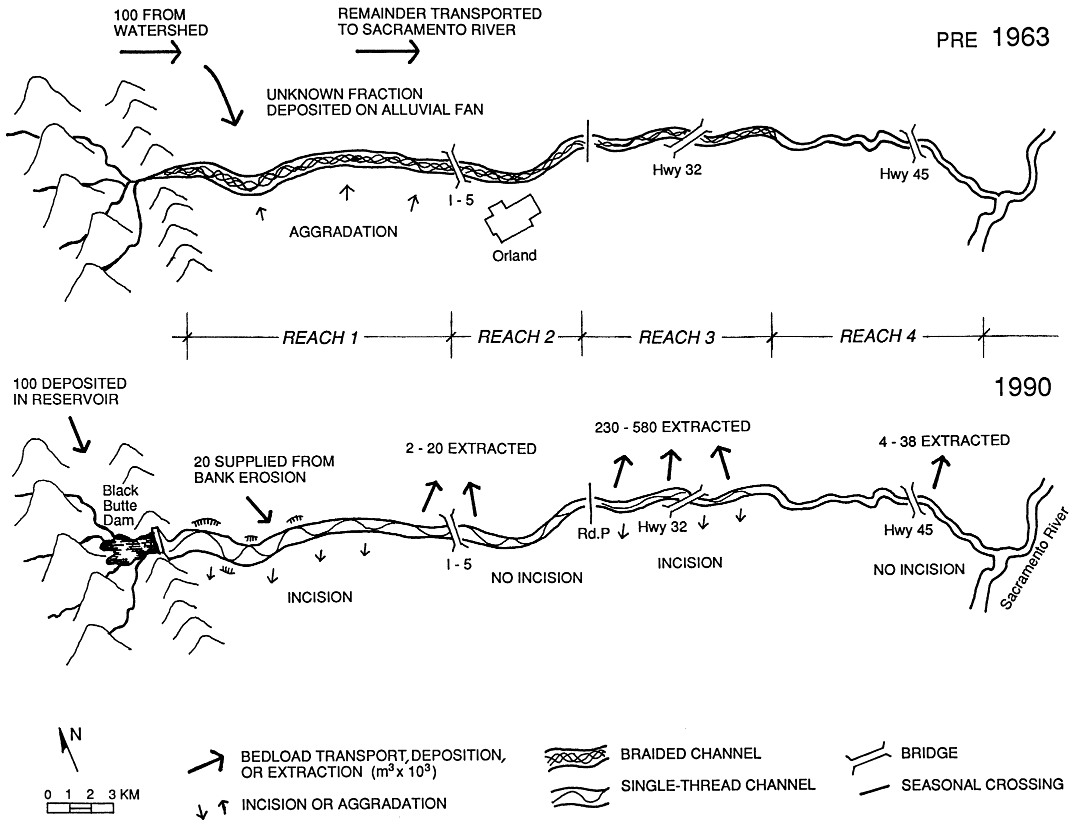

Figure 14. Sediment budget for Stony Creek, California. (Reprinted from Kondolf and Swanson 1993, used by permission of Spring-Verlag, New York.)

A more subtle but potentially significant effect is the increased mobility of the gravel bed if the pavement (the active coarse surface layer) (Parker and Klingeman 1982) is disrupted by mining. Similarly, removal of gravel bars by instream mining can eliminate the hydraulic control for the reach upstream, inducing scour of upstream riffles and thus washout of incubating salmon embryos (Pauley and others 1989).

Secondary Effects of Instream Mining

Among the secondary effects of instream mining are reduced loading of coarse woody debris in the channel, which is important as cover for fish (Bisson and others 1987). Extraction (even bar skimming at low extraction rates) typically results in a wider, shallower streambed, leading to increased water temperatures, modification of pool-riffle distribution, alteration of intergravel flow paths, and thus degradation of salmonid habitat.

Resolving the Effects of Instream Mining from Other Influences

In many rivers, several factors potentially causing incision in the channel may be operating simultaneously, such as sediment trapping by dams, reduced channel migration by bank protection, reduced overbank flooding from levees, and instream mining. However, in many rivers the rate of aggregate extraction is an order of magnitude greater than the rate of sediment supply from the drainage basin, providing strong evidence for the role of extraction in causing channel change. On Stony Creek, the incision produced by Black Butte Reservoir could be clearly distinguished from the effects of instream mining at the Highway 32 bridge by virtue of the distinct temporal and spatial patterns of incision. The dam-induced incision was pronounced downstream of the reservoir soon after its construction in 1963. By contrast, the instream mining (at rates exceeding the predam sediment supply by 200%–600%, and exceeding the postdam sediment supply by 1000%–3000%) produced incision of up to 7 m centered in the mining reach near the Highway 32 bridge, after intensification of gravel mining in the 1970s (Kondolf and Swanson 1993) (Figure 14).

Management of Instream Gravel Mining

Instream mining has long been prohibited in the United Kingdom, Germany, France, the Netherlands, and Switzerland, and it is being reduced or prohibited in many rivers where impacts are apparent in Italy, Portugal, and New Zealand. In the United States and Canada, instream mining continues in many rivers, despite increasing public opposition and recognition of environmental effects by regulatory agencies. Instream mines continue to operate illegally in many places, such as the United States (Los Angeles Times 1992) and Taiwan.

Strategies used to manage instream mining range widely, and in many jurisdictions there is no effective management. One strategy is to define a redline, a minimum elevation for the thalweg (the deepest point in a channel cross section) along the river, and to permit mining so long as the bed does not incise below this line (as determined by annual surveys of river topography). The redline approach addresses a problem common to many permits in California, which have specified that extraction is permitted ''*x* feet below the channel bed'' or only down to the thalweg, without stating these limits in terms of actual elevations above a permanent datum. Thus the extraction limits have migrated vertically downward as the channel incises.

Another approach is to estimate the annual bedload sediment supply from upstream (the replenishment rate) and to limit annual extraction to that value or some fraction thereof, considered the ''safe yield.'' The replenishment rate approach has the virtue of scaling extraction to the river load in a general way, but bedload transport can be notoriously variable from year to year. Thus, this approach is probably better if permitted extraction rates are based on new deposition that year rather than on long-term average bedload yields. More fundamentally, however, the notion that one can extract at the replenishment rate without affecting the channel ignores the continuity of sediment transport through the river system. The mined reach is the ''upstream'' sediment source for downstream reaches, so mining at the replenishment rate could be expected to produce hungry water conditions downstream. Habitat managers in Washington state have sought to limit extraction to 50% of the transport rate as a first-cut estimate of safe yield to minimize effects upon salmon spawning habitat (Bates 1987).

Current approaches to managing instream mining are based on empirical studies. While a theoretical approach to predicting the effects of different levels of gravel mining on rivers would be desirable, the inherent complexity of sediment transport and channel change makes firm, specific predictions impossible at present. Sediment transport models can provide an indication of potential channel incision and aggradation, but all such models are simplifications of a complex reality, and the utility of existing models is limited by unreliable formulation of sediment rating curves, variations in hydraulic roughness, and inadequate understanding of the mechanics of bed coarsening and bank erosion (NRC 1983).

In 1995, the US Department of Transportation issued a notice to state transportation agencies indicating that federal funds will no longer be available to repair bridges damaged by gravel mining, a move that may motivate more vigorous enforcement of regulations governing gravel mining in rivers by states.

Floodplain Pit Mining

Floodplain pit mining transforms riparian woodland or agricultural land into open pits, which typically intersect the water table at least seasonally (Figure 15). Floodplain pit mining has effectively transformed large areas of floodplain into open-water ponds, whose water level commonly tracks that of the main river closely, and which are commonly separated from the active channel by only a narrow strip of unmined land. Because the pits are in close hydrologic continuity with the alluvial water table, concerns are often raised that contamination of the pits may lead to contamination of the alluvial aquifer. Many existing pits are steep-sided (to maximize gravel yield per unit area) and offer relatively limited wetlands habitat, but with improved pit design (e.g., gently sloping banks, irregular shorelines), greater wildlife benefits are possible upon reclamation (Andrews and Kinsman 1990, Giles 1992).

In many cases, floodplain pits have captured the channel during floods, in effect converting formerly off-channel mines to in-channel mines. Pit capture occurs when the strip of land separating the pit from the channel is breached by lateral channel erosion or by overflowing floodwaters. In general, pit capture is most likely when flowing through the pit offers the river a shorter course than the currently active channel.

When pit capture occurs, the formerly off-channel pit is converted into an in-channel pit, and the effects of instream mining can be expected, notably propagation of incision up- and downstream of the pit. Channel capture by an off-channel pit on the alluvial fan of Tujunga Wash near Los Angeles created a nickpoint that migrated upstream, undermining highway bridges (Scott 1973). The Yakima River, Washington, was captured by two floodplain pits in 1971, and began undercutting the highway for whose construction the pits had been originally excavated (Dunne and Leopold 1978). High flows on the Clackamas River, Oregon, in 1996 resulted in capture of an off-channel pit and resulted in 2 m of incision documented about 1 km upstream

Figure 15. Floodplain pit along Cottonwood Creek near Redding, California. (Photograph by author, January 1989.)

Figure 16. Incision of Clackamas River approximately one mile upstream of captured gravel pit near Barton, Oregon. The three men on the right are standing on the bed of a side channel that formerly joined the mainstem at grade, but is now elevated about 2 m above the current river bed, after upstream migration of a nickpoint from the gravel pit. View upstream. (Photograph by author, April 1996.)

(Figure 16) and caused undermining of a building at the gravel mine site (Figure 17).

Off-channel gravel pits have been used successfully as spawning and rearing habitat for salmon and trout in Idaho (Richards and others 1992) and on the Olympic Peninsula of Washington (Partee and Samuelson 1993). In warmer climates, however, these off-channel pits are likely to heat up in the summer and provide habitat for warm-water fish that prey on juvenile salmonids. During floods, these pits may serve as a source of warm-water fish to the main channel, and juvenile salmon can become stranded in the pits. The Merced River, California, flows through at least 15 gravel pits, of which seven were excavated in the active channel, and eight were excavated on the floodplain and subsequently captured the channel (Vick 1995). Juvenile salmon migrating towards the ocean become disoriented in the quiet water of these pits and suffer high losses to predation by largemouth and smallmouth bass (*Micropterus salmoides* and *M. dolomieui*). On the nearby Tuolumne River, a 1987 study by the California Department of Fish and Game estimated that juvenile chinook salmon migrating oceanward suffered 70% losses to predation (mostly in gravel pits) in the three days required to traverse an 80-km reach from LaGrange Dam to the San Joaquin River (EA 1992). To reduce this predation problem, funding has been allocated to repair breached levees at one gravel pit on the Merced River at a cost of

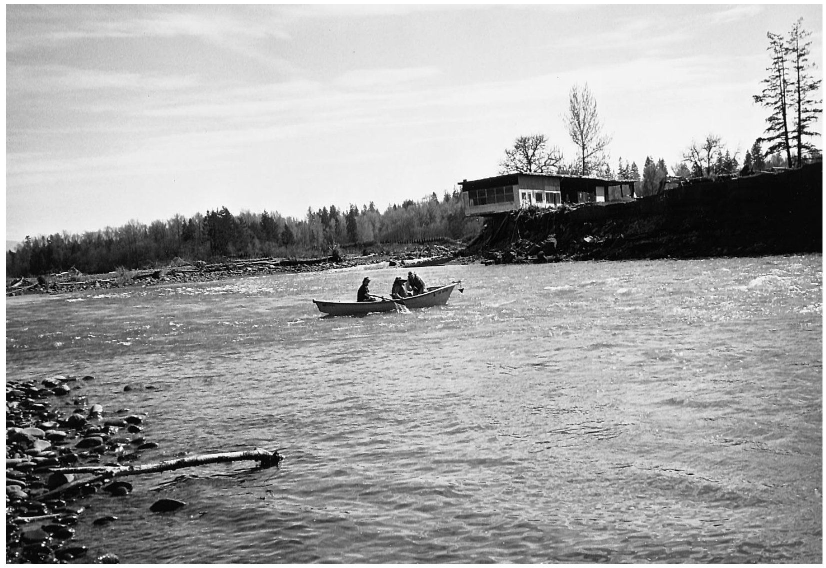

Figure 17. Building undercut by bank erosion as the Clackamas River flows through a captured gravel pit near Barton, Oregon. (Photograph by the author, April 1996.)

US$361,000 (Kondolf and others 1996a), and refilling of two pits on the Tuolumne River has been proposed at a cost of $5.3 million (McBain and Trush 1996).

Aggregate Supply, Quality, and Uses

Aggregates can be obtained from a wide variety of sources (besides fluvial deposits), such as dry terrace mines, quarries (from which rock must be crushed, washed, and sorted), dredger tailings, reservoir deltas, and recycling concrete rubble. These alternative sources usually require more processing and often require longer transportation. Although their production costs are commonly higher, these alternative sources avoid many impacts of riverine extraction and may provide other benefits, such as partially restoring reservoir capacity lost to sedimentation and providing opportunities for ecological restoration of sterile dredger tailings.

In California, most aggregate that has been produced to date has been PCC-grade aggregate from instream deposits or recent channel deposits in floodplains. These deposits were viewed as virtually infinite in supply, and these high-grade aggregates have been used in applications (such as road subbase) for which other, more abundant aggregates (e.g., crushed rock from upland quarries) would be acceptable. Given that demand for aggregate commonly exceeds the supply of sand and gravel from the catchment by an order of magnitude or more, public policy ought to encourage reservation of the most valuable aggregate resources for the highest end uses. PCC-grade instream gravels should be used, to the extent possible, only in applications requiring such high-quality aggregate. Upland quarry and terrace pit sources of lower-grade aggregate should be identified, and alternative sources such as mining gold dredger tailings or reservoir accumulations, should be evaluated. Wherever possible, concrete rubble should be recycled to produce aggregate for many applications.

Reservoir sediments are a largely unexploited source of building materials in the United States. In general, reservoir deposits will be attractive sources of aggregates to the extent that they are sorted by size. The depositional pattern within a reservoir depends on reservoir size and configuration and the reservoir stage during floods. Small diversion dams may have a low trap efficiency for suspended sediments and trap primarily sand and gravel, while larger reservoirs will have mostly finer-grained sand, silt, and clay (deposited from suspension) throughout most of the reservoir, with coarse sediment typically concentrated in deltas at the upstream end of the reservoir. These coarse deposits will extend farther if the reservoir is drawn down to a low level when the sediment-laden water enters. In many reservoirs, sand and gravel occur at the upstream end, silts and clays at the downstream end, and a mixed zone of interbedded coarse and fine sediments in the middle.

Sand and gravel are mined commercially from some debris basins in the Los Angeles Basin and from Rollins Reservoir on the Bear River in California. In Taiwan, most reservoir sediments are fine-grained (owing to the caliber of the source rocks), but where coarser sediments are deposited, they are virtually all mined for construction aggregate (J. S. Hwang, Taiwan Provincial Water Conservancy Bureau, Taichung City, personal communication 1996). In Israel, the 2.2-km-long Shikma Reservoir is mined in its upper 600 m to produce sand and gravel for construction aggregate, and in its lower 1 km to produce clay for use in cement, bricks, clay seals for sewage treatment ponds, and pottery (Laronne 1995, Taig 1996). The zone of mixed sediments in the mid-section of the reservoir is left unexcavated and vegetated so it permits only fine-grained washload to pass downstream into the lower reservoir, thereby ensuring continued deposition of sand and gravel in the upstream portion of the reservoir and silt and clay in the downstream portion. The extraction itself restores some of the reservoir capacity lost to sedimentation. Similarly, on Nahal Besor, Israel, the off-channel Lower Rehovot Reservoir was deliberately created (to provide needed reservoir storage) by gravel mining. Water is diverted into the reservoir through a spillway at high flows, as controlled by a weir across the channel (Cohen 1996).

Extraction of reservoir sediments partially mitigates losses in reservoir capacity from sedimentation. Because of the high costs and practical problems with construction of replacement reservoir storage and/or mechanical removal of sediment, restoration of reservoir capacity may be seen as one of the chief benefits from mining aggregate and industrial clays from reservoirs. If these benefits are recognized, mining reservoir deposits may become more economically attractive in the future, especially if the environmental costs of instream and floodplain mining become better recognized and reflected in the prices of those aggregates. In the United States, construction of reservoirs was often justified partially by anticipated recreational benefits, and thus reservoir margins are commonly designated as recreation areas, posing a potential conflict with an industrial use such as gravel mining. Furthermore, wetlands may form in reservoir delta deposits, posing potential conflicts with regulations protecting wetlands.

Conclusions

Comprehensive management of gravel and sand in river systems should be based on a recognition of the natural flow of sediment through the drainage network and the nature of impacts (to ecological resources and to infrastructure) likely to occur when the continuity of sediment is disrupted. A sediment budget should be developed for present and historical conditions as a fundamental basis for evaluation of these impacts, many of which are cumulative in nature.

The cost of sediment-related impacts of existing and proposed water development projects and aggregate mines must be realistically assessed and included in economic evaluations of these projects. The (very real) costs of impacts such as bridge undermining, loss of spawning gravels, and loss of beach sand are now externalized, borne by other sectors of society rather than the generators of the impacts. The notion of sediment rights (analogous to water rights) should be explored as a framework within which to assess reservoir operations and aggregate mining for these impacts.

Sediment pass-through should be undertaken in reservoirs (where feasible) to mimic the natural flux of sediment through the river system. Pass-through should be done only during high flows when the sediment is likely to continue dispersing downstream from the reservoir. The cost of installing larger low-level outlets (where necessary) on existing dams will generally be less than costs of mechanical removal of sediments over subsequent decades. In larger reservoirs where sediment cannot be passed through a drawn-down reservoir, alternative means of transporting the gravel and sand fractions around (or through) reservoirs using tunnels, pipes, or barges should be explored.

Flushing flows should be evaluated not only in light of potential benefits of flushing fine sediments from mobilized gravels, but also the potential loss of gravel from the reach due to downstream transport.

The regional context of aggregate resources, market demand, and the environmental impacts of various alternatives must be understood before any site-specific proposal for aggregate extraction can be sensibly reviewed. In general, effects of aggregate mining should be evaluated on a river basin scale, so that the cumulative effects of extraction on the aquatic and riparian resources can be recognized. Evaluation of aggregate supply and demand should be undertaken on the basis of production–consumption regions, encompassing the market for aggregate and all potential sources of aggregate within an economical transport distance.

The finite nature of high-quality alluvial gravel resources must recognized, and high-quality PCC-grade aggregates should be reserved only for the uses demanding this quality material (such as concrete). Alternative sources should be used in less demanding applications (such as road subbase). The environmental costs of instream mining should be incorporated into the price of the product so that alternative sources that require more processing but have less environmental impact become more attractive.

Instream mining should not be permitted in rivers downstream of dams by virtue of the lack of supply from upstream or in rivers with important salmon spawning (unless it can be shown that the extraction will not degrade habitat).

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Erosion and sedimentation on the Russian Plain, part 1: contemporary processes

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Abstract:

During the 1970s and 1980s the techniques of tillage and the area of cultivation on the Russian Plain remained virtually unchanged. Therefore, it is possible to assess both the rate and forms of erosion and sedimentation over almost all of the plain for this period of several decades. Using the SHI model and USLE, with coefficients derived for Russian conditions, observed gully density, area and volume, and a morphogenetic classification of streams, it has been possible to produce an assessment of the current state of erosion and sedimentation. The geographic patterns of both the rates and types of erosion and sedimentation are presented and partially explained. This assessment will be of considerable value as a 'baseline' against which to assess future changes as the area of cultivation and the methods of farming change, as well as to assess historical erosion and deposition. Copyright © 2003 John Wiley & Sons, Ltd.

KEY WORDS sheet and rill erosion; gully formation; small rivers sedimentation; Russian Plain

INTRODUCTION

Erosion in river catchments frequently occurs most rapidly during times of substantial increase in the cultivated area or of change in tillage technology and the crops cultivated. During the period from the 1970s to the 1980s, these factors were virtually unchanged on the Russian Plain. Therefore, it is possible to evaluate both the magnitude and the forms of erosion and sedimentation over a large area during a period of relatively little change.

The recent major social changes in the countries of the former USSR, and changes in policy in the use of land and water resources in the newly established states, have led to changes in erosion and sedimentation. Thus, the state of erosion in the Russian Plain in the 1970s and 1980s, as documented in this paper, will provide a baseline for future studies of erosion and sedimentation under new management regimes. Investigations of historical changes in erosion and deposition rates during the period of agriculture also require a reference level, which is best provided by studies of a relatively stable system.

SHEET AND RILL EROSION ON AGRICULTURAL LAND

Methods of investigation

In the Laboratory of Soil Erosion and Fluvial Processes of the Geographical Faculty at Moscow University, a series of 1 : 1 500 000 and 1 : 500 000 maps of erosion-prone regions has been compiled for the whole of the USSR, based on quantitative accounting of erosion factors. (A map of Erosion-prone Areas of the Non-Black Earth Region of the RSFSR has been published by GUGK (1980); those for other areas are in manuscript form.) To calculate soil loss from rainfall, a modified version of the universal soil loss equation (USLE) was

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used (Wischmeier and Smith, 1978). Soil loss during snow melt was calculated using a modified (Larionov, 1993) version of the model of the State Hydrological Institute (SHI model; Anon., 1979). In the case of the USLE the main improvement was related to the relief factor, for which a new formula was developed. Modification of the SHI model involved incorporation of improved methods to calculate the soil erodibility and crop rotation coefficients, runoff depth for the snow-melt period, and the slope length and gradient factors.

The principle of superposition of the erosion factors was used to map erosion rates at the scales 1 : 1 500 000 and 1 : 500 000. Each factor of the USLE or SHI model was mapped separately. The erosivity factor R was calculated for all meteorological stations within the USSR with rainfall intensity measurements. Regional relationships between R and mean annual rainfall depth were established and erosivity was also estimated for stations with rainfall depth measurements. Based on these data, the R factor was mapped using isolines. The soil factor K was calculated directly from the USLE diagram for all areas of different soil type, structure and organic matter content, shown on the Soil Map of the USSR at the 1 : 1 000 000 scale. The vegetation cover factor C was calculated from long-term crop rotation statistics for all administrative districts within the agricultural belt of the former USSR, and seasonal changes in vegetation cover were also taken into account. The same spatial resolution was chosen for the management factor P, which was estimated from State statistics on land management. The most complex approach was associated with calculation of the relief factor LS, which was judged to be the most variable and significant. The agricultural belt was subdivided into morphologically similar units, according to a geomorphologic typology of the USSR. A set of large-scale (1 : 25 000) topographic maps was randomly selected for each unit. Measurements of relief characteristics were performed separately for cultivated and uncultivated lands at 400–600 points to obtain the distribution of the LS factor within the unit and its mean value. This approach for mapping the USLE and SHI model factors, described in detail by Larionov (1993), made it possible to estimate average values of soil loss for relatively large areas, as well as the variation of erosion rates within these areas.

One of the main problems is the need to validate the models used against actual measurements. There are 16 stations in Russia with long-term observations of soil erosion rates during the snow-melt period. At most of these stations, observations have been made on runoff plots characterized by slopes steeper than the typical local landscape. The rates of erosion obtained are also presumed to be higher. Comparison of observed data with those estimated using the SHI model shows (Table I) an acceptable level of accuracy (within 50% relative error) for the forest and forest-steppe zones. The accuracy is much lower for the steppe zone (more than 90% error), where soil erosion is more intensive during rainfall.

There are few long-term experimental observations of rates of soil erosion due to rainfall in Russia. Erosion during rainfall is dominant for the station at Nazarovskaya Hollow in Siberia. Comparison of observed erosion rates with those calculated using the USLE for this station (Bazhenova, 1993) confirms the accuracy of the model for these conditions (Table II).

The estimated erosion rates were also compared with erosion rates derived from sedimentation volumes in small ponds, which where not disturbed during their lifetime. These ponds are located in the lower parts of fields at the gully heads. Usually, all sediment washed out from the fields accumulates in the pond. As soil

Table I. Correlation between observed (O) annual soil erosion rates and those calculated (E) using the SHI model for the snow thaw period for different landscapes of the Russian Plain. (RE = 100 × |O − E|/O is the relative error in all tables)

Location of observation points	Observation period	Type of plot	Landscape	Soil erosion rate (t ha^{-1} year^{-1})		
				O	E	RE (%)
1 Smolensk–Moskovskaya upland	1982–95	Small catchment	Forest	0·9	1·3	44·4
2 Western Ural foothills	1964–91	Runoff plots	Forest	3·5	2·7	22·9
3 Privolzskaya upland	1973–88	Runoff plots	Forest-steppe	1·6	1·45	9·4
4 Kalach upland	1958–83	Runoff plots	Northern steppe	1·9	0·15	92·1

Table II. Correlation between observed (O) annual rain soil erosion rates due to rainfall and those estimated (E) using the USLE for the Nazarovskaya Hollow station, in the steppe zone of Siberia

Part of slope	Soil erosion rate (t ha^{-1} year^{-1})								
	Plot 1			Plot 2			Plot 3		
	O	E	RE (%)	O	E	RE (%)	O	E	RE (%)
Top	0·5	0·47	6·0	0·2	0·25	25·0	0·4	0·22	45·0
Middle	1·2	1·42	18·3	0·8	0·95	18·8	1·3	0·86	33·8
Steep part	—	—		2·5	2·75	10·0	1·1	0·83	24·5
Bottom	—	—		1·1	0·83	24·5	0·2	0·36	80·0

Table III. Comparison of soil erosion rates estimated (E) using both the SHI and USLE models with observed (O) soil erosion rates derived from measurements of the volume of sedimentation in small ponds in the Voronezhskaya oblast' within the Veduga River basin

	Catchment area (km^2)	Relief		Soil erosion rate (t ha^{-1} year^{-1}		RE (%)
		Slope length (m)	Mean gradient (%)	O (from volume of deposition)	E	
1	0·27	500–600	3·4	4·9	5·8	18·4
2	0·068	200–300	5·8	22·3	25	12·1
3	0·148	400–500	3	5·7	6·6	15·8
4	0·063	400–550	6–7	3·2	6·1	90·6
5	0·055	300–400	4–5	2	4·9	145·0
6	0·1	350–450	6–7	6·8	9·7	42·6
7	0·085	700–750	8–9	10·6	11·8	11·3
8	0·208	200–700	5–6	4·6	6·3	37·0
9	0·065	500–600	6–7	4·3	8·7	102·3
10	0·12	300–600	6–7	4·2	8·8	109·5

erosion on these fields was the result of both snow melt and rainfall, the field investigations were compared with erosion rates, estimated using both models (Table III).

The applicability of the empirical formulae and the compatibility of their results have also been checked by field studies on the same catchments using the ^{137}Cs method (Sidorchuk and Golosov, 1996), which demonstrated the necessity to calibrate these models in several cases. Overall, this comparison gave good results for the greater part of the agricultural zone of the Russian Plain.

The spatial distribution of the climatic and land-use factors influencing erosion

The spatial distribution of soil loss factors in an area with such varied climate, soils, relief conditions, as the Russian Plain is extremely complex. Substantial variations in the climatic parameters of the area, including the amount of precipitation and the proportion of rain relative to snow, produce different zonal combinations of fundamentally different forms of erosion: melt-water erosion and rainfall erosion (Figure 1). In the north there is a zone of melt-water erosion (zone I). Further south, zone II is characterized by both melt-water and rainfall erosion. Its northern limit marks the zone where the severity of soil loss from both types of erosion is equal, whereas its southern limit represents the zone where the rate of melt-water erosion is approximately equal to the rate of natural soil formation. The northern limit of zone III, in which rainfall erosion predominates, represents the limit of the zone of irregular snow cover. South of this, melt-water erosion rarely exists in zone IV, and the relative importance of rainfall erosion is very much higher. The most southerly zone (zone V)

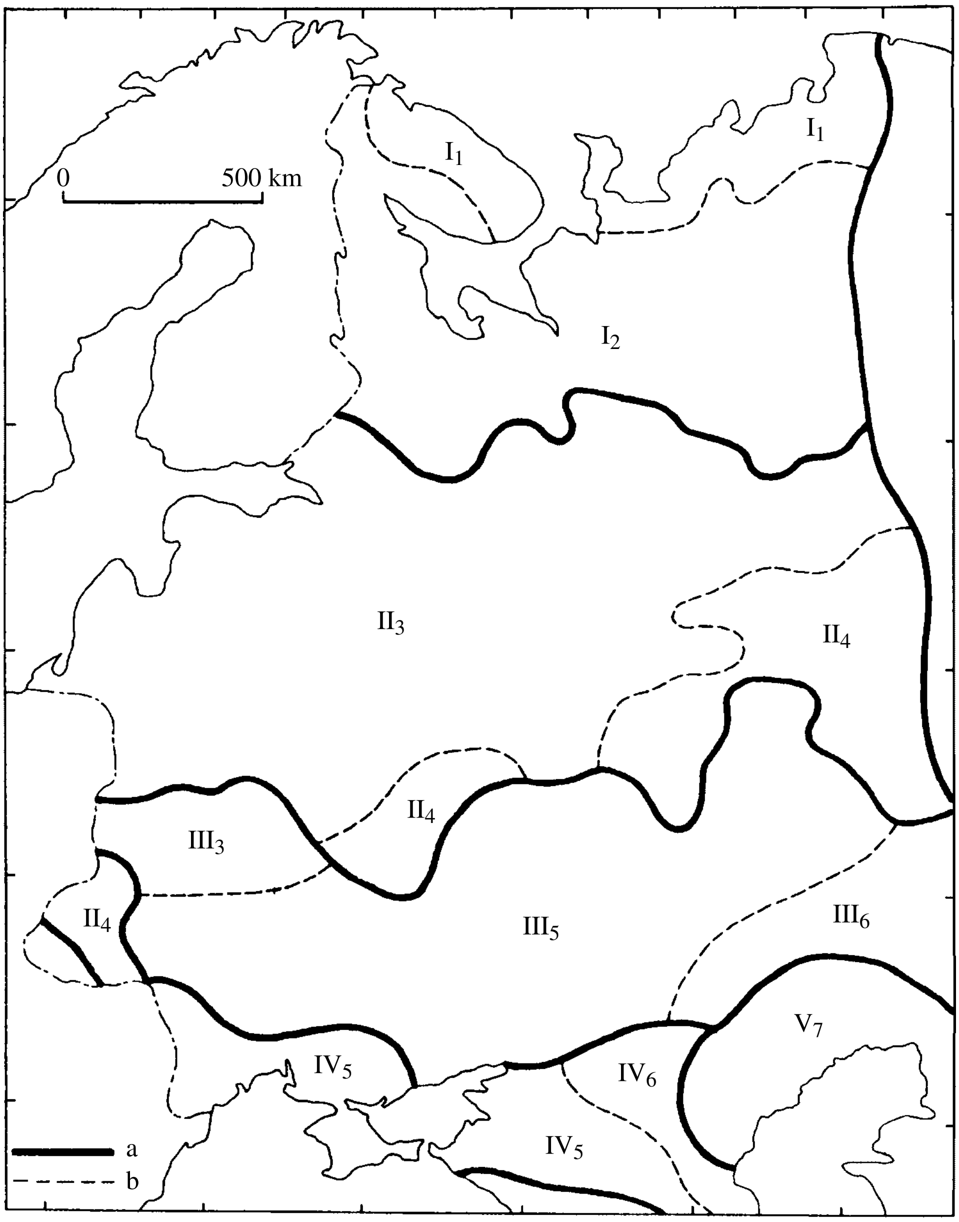

Figure 1. Map of agricultural land on the Russian Plain, showing erosion zoning. (a) Natural erosion zones with predominance of: (I) melt-water erosion; (II) melt-water and rainfall erosion; (III) mainly rainfall erosion; (IV) rainfall erosion without snow melt; (V) occasional erosion, (b) Regions of man-induced erosion: (1) reindeer breeding; (2) patch farming; (3) mixed farming—cultivation and stock-raising, with highly selective land use; (4) intensive tillage with low selectivity; (5) land fully exploited for cultivation; (6) tillage and grazing; (7) grazing and patch cultivation. (a) Boundaries between natural erosion zones; (b) boundaries between the regions of man-induced erosion

is characterized by occasional rainfall erosion and borders the zone where slope erosion is a very rare and extremely short-lived phenomenon.

The next basis for zonation of the erosion status of the Russian Plain is agricultural land use. The location and extent of agriculture, the proportion of tilled land and the relationship between pasture and arable land determine the severity of erosion. For example, in region 1 with reindeer pastures, soil erosion by water will occur only in the highly disturbed oil and gas fields, whilst the pasture itself is subjected mainly to wind erosion if overgrazed. In the patch farming region (region 2) the severity of erosion on cultivated slopes is marked, but the total soil loss is small, because arable land comprises only a few percent of an area, which is mostly forest or tundra. Within the northern region 3 of mixed farming (cultivation and stock-raising) with highly selective land use, the spatial variability of the landscape and the distribution of arable lands and pasture is complex, but the rate of erosion on the arable lands is relatively constant due to the similarity of the terrain selected for farming. In contrast, in regions 4 and 5 with intensive agriculture, arable land comprises up to 80% of the total area, and erosion rates are high and variable.

The distribution of erosion rates on the Russian Plain

The schematic map (Belotserkovskiy *et al*., 1991) shows the average severity of erosion, with subdivision by administrative district (Figure 2). In the Baltic seaboard, the average soil loss from arable land on major uplands is 5–7 t ha^{-1} $year^{-1}$ (in the south 8–9 t ha^{-1} $year^{-1}$), and on lowlands 1·0–1·5 t ha^{-1} $year^{-1}$. In areas with glacial landforms on the uplands it is 10–12 t ha^{-1} $year^{-1}$, whereas on glacial-lake and fluvioglacial plains it is approximately 2 t ha^{1-} $year^{-1}$. Approximately the same relationship between soil loss from uplands and plains is found in the central part of the Russian Plain: i.e. Central Russian Uplands, 7–8 t ha^{-1} $year^{-1}$; Dnieper Valley, 12–14 t ha^{-1} $year^{-1}$; Oka-Don and Dnieper lowlands 0·5–2·0 t ha^{-1} $year^{-1}$. In contrast, the lowest erosion rate, in the middle of the Pripyat' wooded lowland, is less than 0·5 t ha^{-1} $year^{-1}$. The southern uplands stand out as having the highest soil-loss rates (Stavropol' and Volyno-Podol'sk uplands, 15–20 t ha^{-1} $year^{-1}$; Moldavia approximately 22–25 t ha^{-1} $year^{-1}$), whereas the lowlands are characterized by low rates: the Caspian Plain loses less than 0·5 t ha^{-1} $year^{-1}$ (this land is hardly subject to erosion at all), and the central Black Sea Plain, 2 t ha^{-1} $year^{-1}$.

The mean rate of sheet erosion estimated for the arable lands on the Russian Plain is 6·1 t ha^{-1} $year^{-1}$. This amount is comprised of 0·6 t ha^{-1} $year^{-1}$ from melt-water erosion and 5·5 t ha^{-1} $year^{-1}$ from rainfall erosion. On over 22·7% of the arable land, the rate of erosion is less than 0·5 t ha^{-1} $year^{-1}$; on 24·1% it is in the range 0·5–2·0 t ha^{-1} $year^{-1}$; on 23·5% it is in the range 2·0–5·0 t ha^{-1} $year^{-1}$; on 12·6% it is in the range 5·0–10·0 t ha^{-1} $year^{-1}$; on 9·9% it is in the range 10·0–20·0 t ha^{-1} $year^{-1}$; and on 7·2% of the arable land the erosion rate is more than 20·0 t ha^{-1} $year^{-1}$. The calculated annual soil loss on the Russian Plain in the 1970s and 1980s was about 880 million tonnes from $143 \cdot 8 \times 10^6$ ha of arable land and about 50 million tons from $88 \cdot 8 \times 10^6$ ha of pasture.

GULLY EROSION

The method used to map gully erosion

The present state of gully erosion may be described by a density index (number of gullies per unit area of catchment), which provides a picture of the number of gullies and their extent per unit area (Figure 3). The gully density map was produced using information from large-scale (1 : 25 000 and 1 : 100 000) topographic maps (Kosov *et al*., 1989). The entire area of the European part of Russia was subdivided into morphological units. The number and the total length of gullies over 200 m long, developing on plains and uplands no higher than 400 m above sea level, was calculated for each unit directly from randomly selected topographic maps. The number of gullies with a length between 70 and 200 m was calculated for each unit using a regional relationship between the number of larger and smaller gullies, developed for the key areas. The area and the volume of gullies were calculated using regional relationships between these characteristics and the gully type.

The distribution of gullies on the Russian Plain

The Russian Plain may be divided into the following areas, according to the density of gullies.

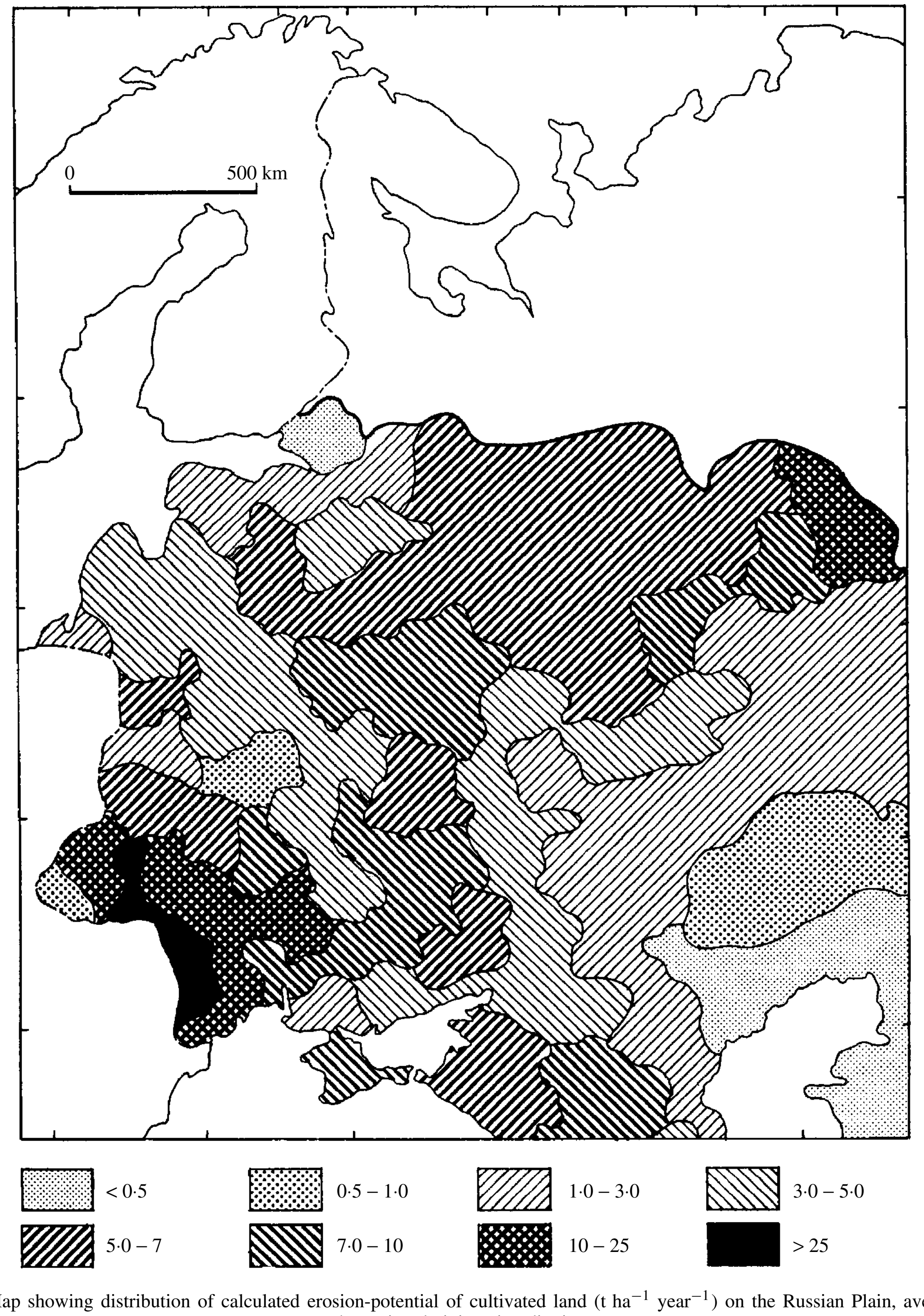

Figure 2. Map showing distribution of calculated erosion-potential of cultivated land (t ha^{-1} year^{-1}) on the Russian Plain, averaged over the main administrative districts

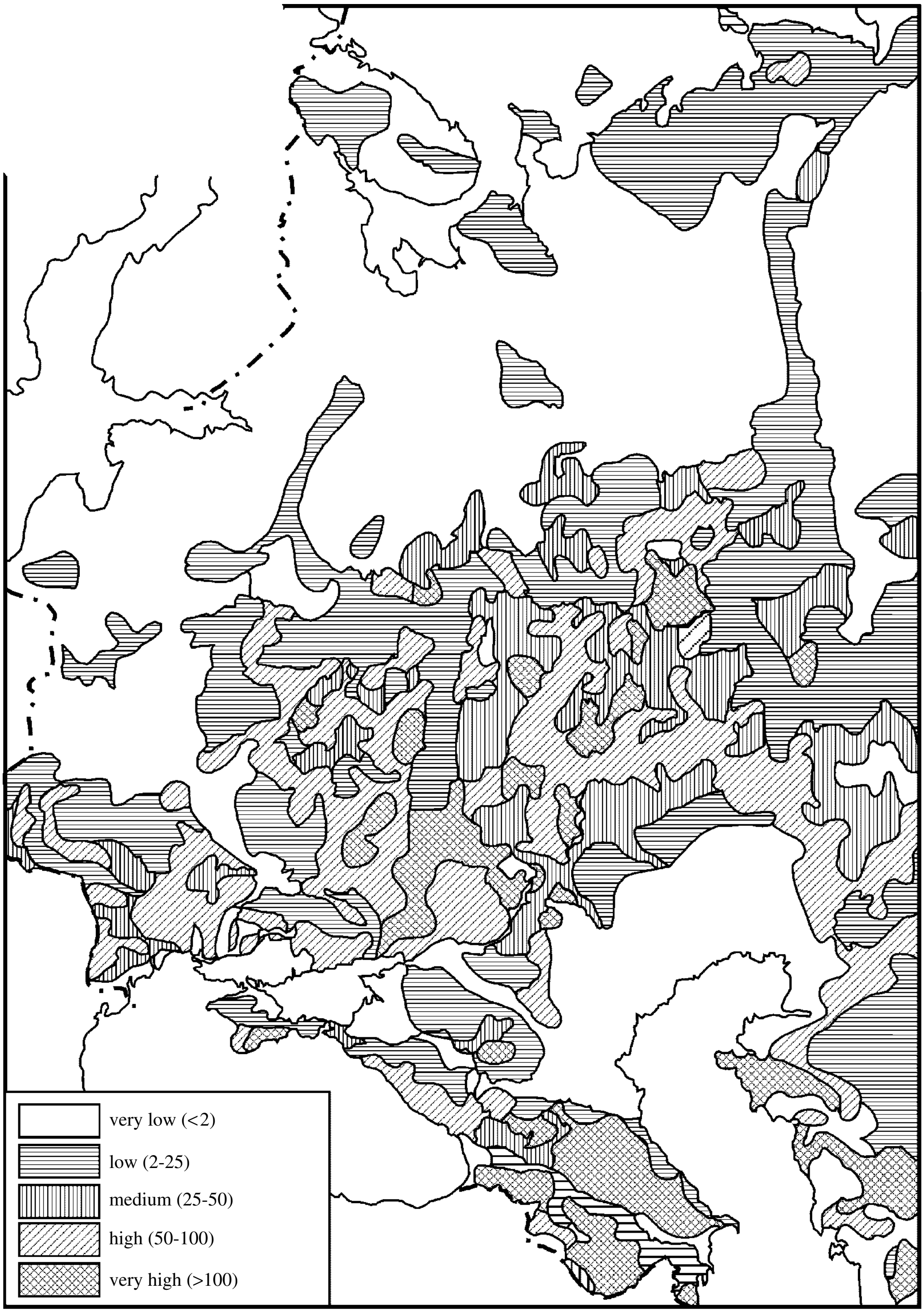

Figure 3. Distribution of gullies on the Russian Plain, showing density categories (number of gullies per 100 km^2)

(a) Areas with very low gully density, where gullies are extremely uncommon and isolated phenomena (<2 gullies/100 km^2). This density is found on: (1) non-tilled or little-tilled land with flat or rolling relief in the northern part (above 57–58 °N) of the forest zone; (2) low-lying plainland with valleys less than 10 m deep. Such regions include Poles'ye, and the greater part of the Dnieper, Black Sea, and Caspian lowlands.
(b) Areas with low gully density, varying between 2 and 25 gullies/100 km^2 over most of the area. Such areas are found in thinly populated regions with little economic development, with low relief, and on flat and forested land. This includes the forest zone south of 57–58 °N; the flatter and more gently sloping parts of the Volyno-Podol'sk uplands, part of the Dnieper lowland plain, the wooded, upland-plain areas of the Smolensk and Central Russian hills; part of the Oka-Don plain; the Kuban' lowlands and a broad forested belt along the western spurs of the Urals to the south of the Kama.
(c) Areas with medium gully density, 25–50 gullies/100 km^2 over the greater part of the area. Most of these areas lie within the forest-steppe and steppe zones, and in the southern part of the forest zone. Such areas are typically found in forested uplands (the Severnyye Uvaly, the Verkhne-Kamskaya uplands); in relatively flat ranges and uplands with shallow relief dissection (the Smolensk Hills, the north western part of the Central Russian uplands, the Volyno-Podol'sk uplands, and others); and on rolling plains (Tambov region, the Oka-Don plain, the western part of the Obshchiy Syrt).
(d) Areas with high gully density, 50–100 gullies/100 km^2 over the greater part of the area. A substantial part of the steppe and wooded steppe zones are in this category. These are mainly areas of advanced development, with relatively favourable natural conditions for gully formation, characterized by deeply dissected relief. Such regions include the central parts of upland country: Volyno-Podol'sk, the Dnieper region, the Central Russian region, and the Volga valley.
(e) Areas with very high gully density, over 100 gullies/100 km^2 over the greater part of the area. These comprise relatively small areas in the middle of upland zones and along river banks, and total no more than 10% of all gullied land.

In general, the forest-steppe and steppe zones, the principal areas of gully formation, are typified by high to very high gully density. The main human factor influencing gully formation in these areas is tillage of almost the entire area. Gully formation in this area is also promoted by natural conditions, including substantial volumes of melt water and rainfall, relatively erodible soils, and greater local relief. Intensive tillage when these areas were first cultivated led to the formation of a gully system that compared with other regions, is of greater extent and density. Gully formation in areas north and south of the steppe and forest-steppe zones is considerably less. In southern regions this is related primarily to the lower volume of runoff, and in the north to the forest cover and the preservation of natural landscapes and terrain.

The mean gully density on the Russian Plain ($5{\cdot}4 \times 10^6$ km^2) is 0·036 km km^{-2}, representing 1 675 000 gullies with a total length of 196 900 km, an area of 1835 km^2 and a total volume of $5{\cdot}9 \times 10^9$ m^3. These gullies were formed mainly during the period of intensive agriculture over the last 300–400 years.

SEDIMENTATION OF SMALL RIVERS

Sedimentation of small rivers results from deposition of sediment eroded from areas of intensive tillage. The characteristics of such sedimentation of small rivers depend on many natural and human factors, including water volume, seasonal flow distribution, lithology, the relief, and the degree of agricultural or other development. Sedimentation is typically found in rivers flowing across plains.

Methods of mapping sedimentation of small rivers

The morphological criteria used to assess the degree of river channel sedimentation were established on the basis of field investigations of more than 150 key sites within the main landscape units on the Russian Plain. Topographic maps at the 1 : 25 000 scale, covering the headwaters of all the rivers on the Russian Plain with a length more than 100 km, were analysed using these criteria and the small rivers (basin area less than 2000 km^2) were classified into the main types, listed below.

Distribution of the main types of small river sedimentation on the Russian Plain

Field studies and map analysis make it possible to pinpoint typical forms of small river sedimentation. Their spatial distribution within the Russian Plain reflects complicated combinations of natural and man-induced conditions. The distinguishing of zones with varying sedimentation forms is based on the predominance of a particular form, or a particular combination of these forms. The following zones may be distinguished (Figure 4):

1. Areas with a predominance of meandering rivers preserved in their natural, non-sedimented, state, with stable, well-defined banks and a dry flood plain. These are found in thinly populated areas with little cultivation, as in the forest zone. Mean channel gradients of 0·2–0·8‰ ensure the transport of the suspended sediments to the river mouth.
2. Areas in which swampy flood-plain-type rivers predominate; the rivers flow in wide relict valleys with very low gradients (0·05–0·15‰). The configuration of channels in swamps is highly erratic. Their width and depth change within very broad limits (15- to 20-fold), and sometimes a channel disappears and water flows across the swamp surface. Natural swamplands are very vulnerable to man-induced sedimentation.
3. Areas with both sedimented and non-sedimented rivers. Here, there is incipient sedimentation of the channels of creeks adjoining major cropland and farming areas, whereas creeks and rivers of the same size flowing through forests and flood plains remain in their natural state.
4. Areas in which most creeks are sedimented, whereas small rivers remain in their natural state. These conditions occur in the south of the forest zone and the forest-steppe zone, where arable land constitutes 70% of the total catchment area. Most of the sediment from the slopes reaches creeks up to 20 km long, where large-scale sedimentation occurs. This reduces deposition downstream in the small rivers. Thus, the creeks and flood plains serve as a buffer between the slopes and the rivers.
5. Areas with sedimentation of all small and some medium-sized rivers. Under the conditions found in the steppe zone (i.e. intensive tillage of catchments, a climate with regular droughts, heavy water use, and well-defined flow peaks), sediment mobilized from the slopes can reach small and medium rivers. The result is that ordinary channels spread into a swampy network, in which only projecting firm dry banks mark the old channel, overgrown with reeds.
6. Areas with sedimentation of swampy flood-plain-type rivers.
7. Areas of local internal drainage, with very low drainage density, as well as riverless areas.

These areas broadly correspond to natural landscape zones. Areas with no sedimentation coincide with the tundra and taiga, with their high runoff coefficient; those with mixed sedimented and unsedimented rivers tend to be related to the mixed and deciduous forest zones; those with sedimentation of the upper reaches often correspond to the forest-steppe; heavily sedimented rivers are found in the steppe zone with a low runoff coefficient; and inland drainage areas coincide with the arid steppe and semi-desert zones. At the same time, however, the distribution of these areas is more complex than the terrain zones, and their limits frequently do not coincide with those of the latter. This may be because the type and level of economic activity does not correspond to the geographical or terrain zones (take, for example, the penetration of agriculture into the taiga), and because of azonal geological and geomorphologic factors. The latter, determine the shape of the longitudinal profiles of rivers, the values of local gradients, and the erosion and sedimentation capacity of watercourses. Areas shaped mainly by neotectonics and geomorphology with swampland-type rivers are scattered randomly over all areas.

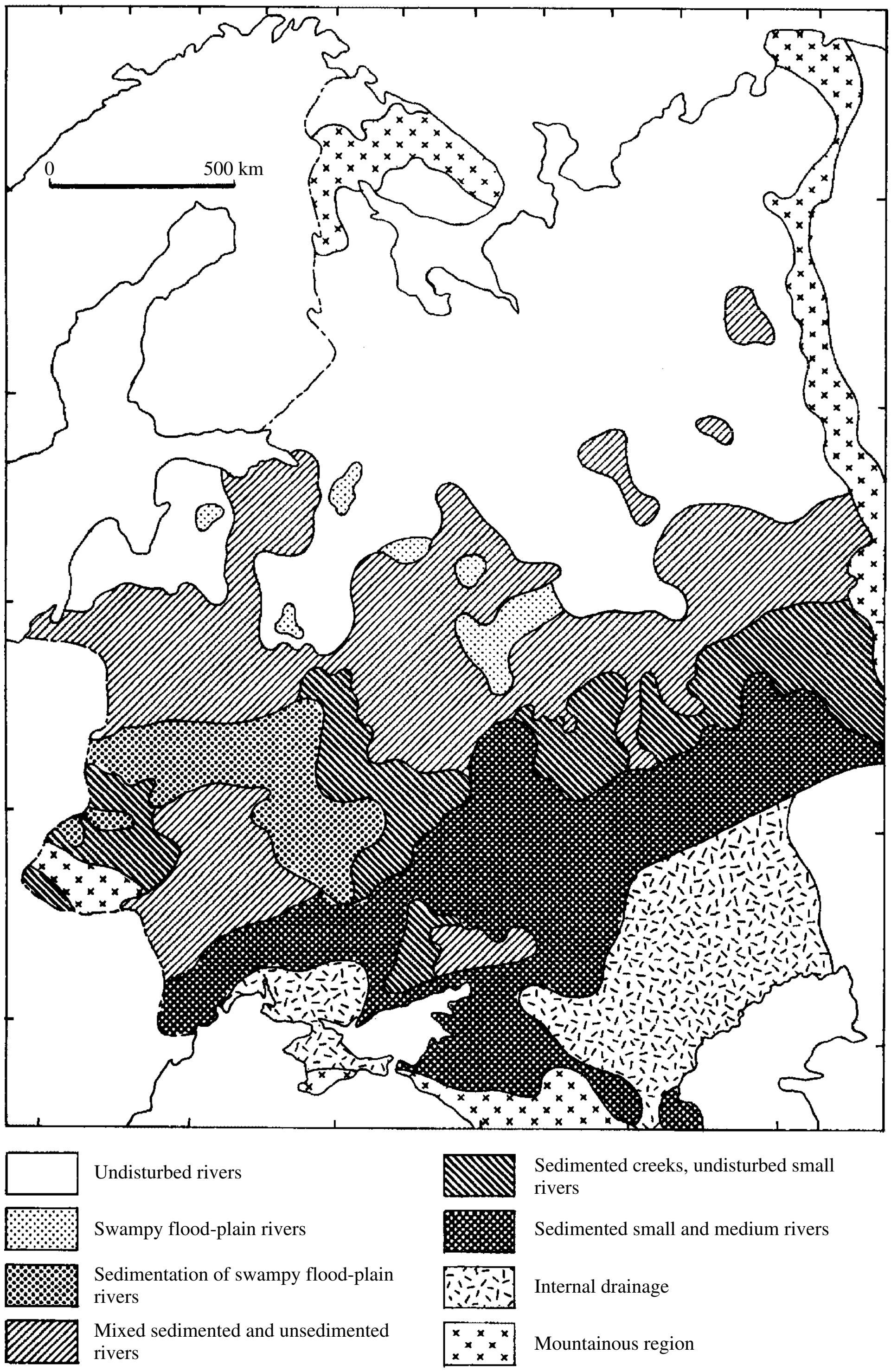

Figure 4. Distribution of typical forms of sedimentation in small rivers in the Russian Plain (for explanation see text)

CONCLUSION

The relative stability of the cultivated area and the minimal change in crop rotation and tillage technology in the 1970s and 1980s have fostered a general stabilization of both erosion and sedimentation rates in the Russian Plain. Under these conditions slope erosion undergoes little change, and is determined by the spatial distribution of erosion factors, and by land-use type and distribution. In lowland areas, soil loss is determined above all by the relief and is little affected by change in climatic factors. Thus, in the Baltic seaboard lowlands the soil loss amounts to 1·0–1·5 t ha^{-1} year^{-1}, in the Oka-Don and Dnieper lowlands to 0·5–2·0 t ha^{-1} year^{-1}, in the Pripyat' wooded heathland and in the Caspian lowlands to less than 0·5 t ha^{-1} year^{-1}. At the same time, in upland terrain with higher soil loss due to relief, variability in erosion rates is determined by climatic factors; in the Baltic seaboard uplands the soil loss amounts to 5·9 t ha^{-1} year^{-1}, in the Central Russian uplands to 7–8 t ha^{-1} year^{-1}, and in the Dnieper uplands to 12–14 t ha^{-1} year^{-1}. The most severe soil erosion occurs on the slopes of the uplands of the southern megaslope of the Russian Plain, in the Stavropol' and Volyno-Podol'sk regions, where mean erosion rates exceed 15–20 t ha^{-1} year^{-1}.

Gully erosion is in general subject to the same laws as slope erosion. Regions with low or very low gully density are primarily those of little or no economic development, as well as bogs and forest. The rolling plains of the steppe and forest-steppe have medium gully density. The highest gully density is found in the central parts of the uplands of the steppe and forest-steppe zones, where the density reaches 50–100 gullies/100 km^2. Under conditions of stable land management, the gully network tends to stabilize. The small number of new gullies, regrowth of vegetation, and the change into the balka stage for most existing gullies is evidence of a new equilibrium in the slope–gully–balka system.

Sedimentation of small rivers, and to some extent of medium-sized rivers, is heaviest in the steppe and forest-steppe zones. The change from gullies into balkas and dry valleys slightly lowers the rate of sedimentation, but the general condition of small rivers in the south of the Russian Plain is little short of disastrous. In the central part of the Russian Plain, creeks that have served as buffers to sedimentation and have protected small and medium-sized rivers from heavy sedimentation suffer heaviest sedimentation.

In the near future a new phase will occur in the intensification of erosion in the Russian Plain, linked with changes in land use. A rapid increase in the cultivated area is taking place in the Russian Non-Black Earth Region. The proportion of inter-tilled crops (potatoes, sugar beet, maize) is increasing in the Central Black-Earth Belt in Russia and in the southern Ukraine. The proportion of small farms with specialized constant crop rotations is increasing and state allocations for soil-conservation measures are diminishing. People with no experience of land husbandry are taking up farming. If a repetition of the general degradation of soils that occurred in the late 19th century, following the abolition of serfdom, is to be prevented, then it is essential that a well-planned state policy of soil conservation education should be pursued, and that a body of laws be designed to promote farming techniques that conserve soils and water resources.

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