Effects of a dredge mining operation on the hydrogeological regime in a humid tropical environment

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Abstract A shallow unconfined aquifer of fair transmissivity comprising highly decomposed crystalline rocks, overlain discontinuously by Pleistocene to Recent alluvial deposits was found to respond to artificially induced recharge from damming of drainage systems. This aquifer underlies five adjacent river basins draining a 246 km^2 area of low to moderate relief on the southwest coast of Sierra Leone, West Africa where alluvial and lateritic deposits of rutile (titanium oxide) are being mined by dredging. A review of pre-existing data and monitoring of water table levels in 23 observation wells and eight dredge-ponds over four successive water years showed that manipulating channels by construction and break down of dams has marked effects on the groundwater regime. Changes were observed in aquifer storage, steepening of the groundwater gradient leading to reversal in natural flow directions and modification of local transient flow systems between surface water bodies and the aquifer.

Los efectos de una operación de minas dragadas sobre el régimen hidrogeológico dentro de un ambiente húmedo y tropical

Resumen Un aquífer poco profundo y ilimitado de transmisbilidad regular el cual constando de rocas cristalinas y muy descompuestas las cuales sobrepuestas discontinuamente desde Pleistoceno hasta Recientes depósitos aluviales se demostrós a responder al recargar producido artificialmente del poner un dique al sistema de drenaje. Este aquífer está en la base de cinco contiguas cuencas de río drenando a un área relieve bajo hasta relieve moderado de 246 km^2 en la costa sudoeste de Sierra Leone, África del oeste donde depósitos aluviales y lateritos de rútilo (titanio óxido) se explotan por dregar. Un análisis de datos existentes y el controlar de los niveles de la capa freática en 23 pozos de vigilacia y ocho estanques hechos por dregar durante cuatro años sucesivos de agua señalaron que el manipular de los canales por el construir y derribar de preses tiene resultados profundos sobre el régimen del agua subterránea. Los cambios en el almacenamiento del aquífer, el escarpar del gradiente del agua subterránea produciendo una inversión en las direcciones del flujo natural y la modificación de los sistema transitorios de flujo entre las áreas superficial de agua y el aquífer fueron observados.

INTRODUCTION

Alluvial and lateritic deposits of rutile (titanium dioxide) occurring as discrete bodies, are presently being mined over a 246 km^2 area on the southwest coast of Sierra Leone, West Africa, approximately 9°N of the Equator. This area comprises the river basins of the Tikote, Kokpoi, Lanti, Yambei and Kopa, and minor stream catchments of Gangama and Semabu, all sub-basins of the Gbangbaia and Jong River systems. They range in size from 10 to 75 km^2. The rivers rise in the Gbangbama and Imperi hills with elevations up to 320 m. With the exception of the Tikote which flows easterly into the Jong, all follow northeast–southwest tectonic lines of weakness through undulating plains at 60 m, to coastal plains at 15 m a.m.s.l. The rutile is derived from highly fractured, 2.1×10^9 year-old gneisses of the Kasila Group, part of the West African craton (Claus *et al.*, 1972), that have been intensely weathered under a humid tropical climate with distinct wet and dry seasons May–October and November–April respectively. Annual average rainfall in the region is 3000 mm.

The deposits are mined sequentially by dredging, which requires that the ore be put under water. As such, the river systems with which the rutile formations are contiguous are dammed to create reservoirs (dredge ponds) within which the equipment can operate. At present the fourth of five main deposits is being mined in the Lanti basin. According to Pratt & Johnson (1991), each of the deposits have been worked at different pond elevations due to topographic variations over the area and the physical limitations of the dredge.

The required pond level is controlled by spillways on the numerous laterite dams constructed. Figure 1 shows locations of ponds, dams and spillways and observation wells in April 1992. Dams B5 and B6 impound mined out Bamba-Belebu pond. Dams P3, P4, P5, P6 and P8 are located on the Tikote drainage system in which the Pejebu and part of the Mogbwemo deposits were worked. Bunds B0, B1, B2 and dam C1/C2 maintained water levels along the Lanti canal route over River Kokpoi, via which mining equipment was moved to the central Lanti pond, impounded by dams C3 and L1/L2. Many smaller dams and bunds have also been constructed to facilitate the containment process and to create reservoirs for domestic and other uses. For comparative purposes, the drainage configuration prior to the implementation of mining in 1964 is shown in Fig. 2.

In order to move dredge mining operations from one deposit to another, dams are continuously being built up, broken down or reconstructed to control water levels at various stages of mining by spilling excess water or channelling surplus water to adjacent containment areas. These modifications ensure that the dredge remains in the optimum depth of water at all times. This manipulation of the hydrological regime has modified fluctuation of water levels in wells (which under normal circumstances are controlled by seasonal climatic changes), created artificial changes in storage and affected the natural transient flow system between surface and groundwater. Reversals in groundwater flow directions have also occurred.

HYDROGEOLOGICAL CONDITIONS IN THE STUDY AREA

As part of an overall water management and environmental impact assessment study of the area commissioned by the mining company and carried out by Environmental and Scientific Consulting Group (ESCG), bimonthly water levels were measured

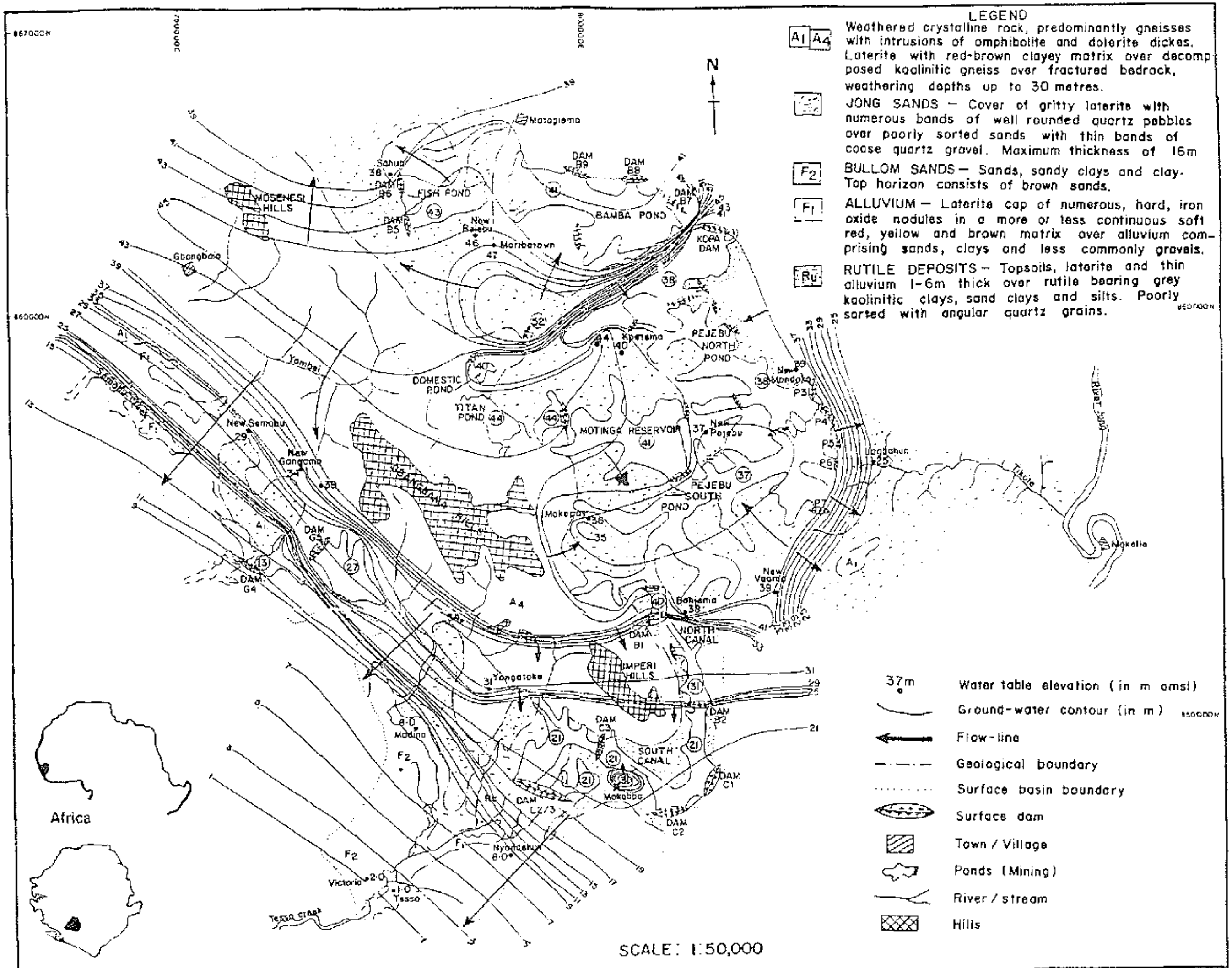

Fig. 1 Hydrogeological map of study area showing location of ponds, dams and observation wells.

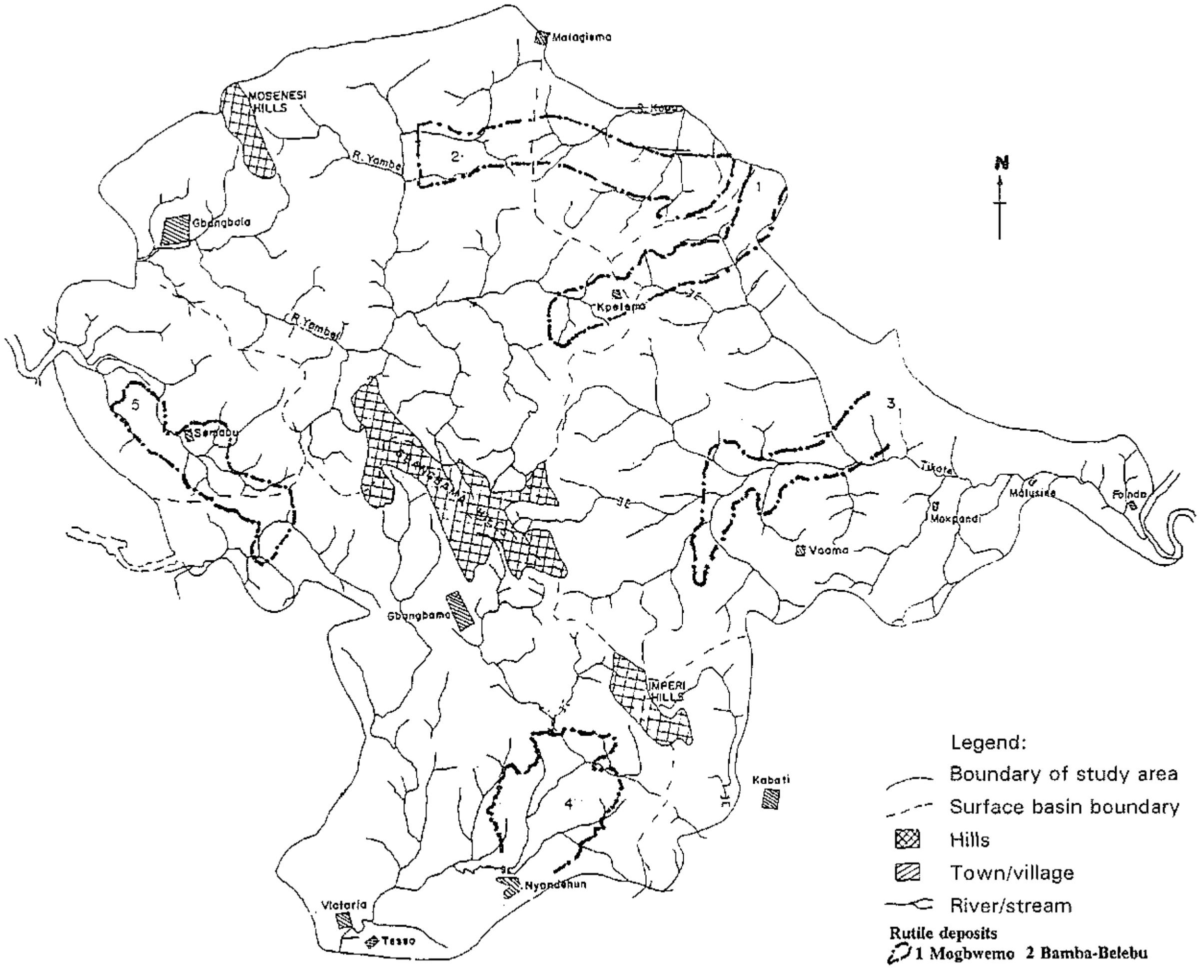

Fig. 2 Drainage map of study area prior to mining.

over four successive water years (1990–1994) in 23 one metre diameter hand-dug wells used for village water supply. The wells, evenly distributed over the study area, vary in depth from 6.3 m below ground level at Kpetema to 20.6 m at Gbangbama, with an average depth of 11.6 m.

The ore bodies themselves constitute a part of the continuous, unconfined aquifer comprising superficial Pleistocene to Recent alluvial deposits, discontinuously developed over decomposed Archaen kaolinitic gneisses with occasional intrusions of granitic rocks, quartz veins, pegmatite, amphibolite and dolerite dikes. Together they make up an interbedded sequence of unconsolidated sands, clays and silts with gravel horizons acting as a single hydraulic entity over fractured bedrock. To the extreme southwest around Lanti however, the deposits overlie sands, clays and silts of the Pleistocene Bullom Group.

Vertical electrical soundings, carried out in the Tikote basin by Akiwumi (1988), indicate that average depth to basement is 23 m but may reach 71 m in the vicinity of a fracture. Stanaway (1986) and Boli (personal communication) based on company drilling operations, have suggested that in the Lanti area depth to basement is greater where the ore rests on the Bullom Group. This assumption is reasonable in the light of the fact that Strasser-King (1979) and Astier (1980) have established that north of the region the Bullom Group attains thicknesses of up to 120 m.

Transmissivity values for these formations based on pumping tests carried out by Akiwumi (1991) are in the range of 152 m^2 day^{-1}. The average depth to dry season water table is 9 m, varying from 3.2 m at New Pejebu to 16.1 m at Gbangbama. The natural seasonal fluctuation of the water table averages 2.5 m, with wells at basin boundaries showing greater fluctuations. Wells affected by the mining process may show anomalous variations. Table 1 gives some basic data on the observation wells.

EFFECTS OF DAMMING

Artificial changes in storage and water table fluctuations

Marked changes in water levels were observed in some wells in direct response to damming. In the Tikote drainage system, where 38.5% of the area has been ponded, an increase in storage was observed between 1987 and 1989. During field studies carried out in June 1987, prior to the creation of Pejebu South pond, depths to water table of 6.1 m and 12.2 m were measured at New Pejebu and New Vaama respectively. These figures compare to 2.9 and 10.2 m recorded in June 1990 during follow-up studies, when mining was on-going in Pejebu pond. Rainfall variations alone, which from analysis of past records are less than 15% from year to year, could not account for the differences.

Pejebu well, sited in an area of low topography and completely surrounded by ponds, was more severely affected. Thereafter, water levels rose and fell according to natural variations in annual recharge as shown in Fig. 3. Levels show the characteristic rise as the wet season progresses, peaking in August–September at the

Table 1 Basic data on observation wells.

Basin	Well location	Well depth (m)	Topographic elevation (m a.m.s.l.)	Peak wet season water elevation, August–September (m a.m.s.l.)				Peak dry season water elevation, April–May (m a.m.s.l.)			
				1990	1991	1992	1993	1991	1992	1993	1994
Tikote	Bonjema #	10.7	44.2	39.7	39.5	38.9	38.5	38.0	38.0	37.3	37.0
	Kpetema	6.3	50.3	46.9	46.5	46.7	46.6	44.2	44.4	44.7	44.8
	Jagbahun #	10.2	30.5	24.7	24.7	24.0	23.0	25.0	25.0	23.2	22.5
	Mokepay	11.9	44.2	38.3	38.2	38.5	38.3	35.8	35.6	34.8	35.1
	Motinga	10.4	42.7	35.4	35.3	-	-	32.9	33.0	-	-
	New Mondoko	13.7	45.7	39.6	39.4	39.2	39.3	38.8	38.5	38.3	38.4
	New Ndendemoia #	15.6	52.0	44.5	44.8	44.6	44.7	dry	40.0	41.6	38.0
	New Pejebu	11.6	40.5	39.7	39.3	35.3	34.1	37.4	36.9	31.5	30.5
	New Vaama #	15.7	52.4	45.9	45.3	45.0	45.0	39.9	39.4	39.1	38.8
Yambei	Sahun	7.7	44.2	38.6	38.7	38.9	38.8	38.3	37.8	39.1	41.1
	Junctoila	13.7	51.8	-	47.2	47.5	47.3	42.4	42.7	42.0	42.7
	Moriba Town	11.9	55.8	50.2	50.7	50.4	50.6	47.3	47.5	47.8	47.7
	New Bamba/Belebu #	9.4	53.3	48.4	48.1	48.2	48.4	46.2	dry	45.8	45.7
Gangama	New Gangama	13.7	44.2	40.1	40.5	40.3	40.2	34.4	34.4	34.2	33.9
Semabu	New Semabu #	13.4	38.0	*	31.8	31.9	31.7	*	29.0	29.0	28.9
Lanti	Gbangbama	20.6	50.3	38.7	38.1	38.3	38.5	34.4	34.2	34.5	34.0
	Madina	5.7	13.7	*	11.4	11.6	11.5	*	8.0	8.2	8.8
	Mokabba	11.1	39.6	*	36.0	36.1	36.0	*	30.7	30.9	30.5
	Nyandehun 1	11.4	16.8	*	9.2	9.1	9.3	*	8.4	8.5	8.5
	Nyandehun 2	10.5	15.9	*	10.0	9.8	10.1	*	8.1	8.0	8.1
	Victoria 1	10.9	9.1	3.0	2.7	2.9	2.8	1.0	1.0	1.1	1.1
	Victoria 2	13.9	13.7	3.8	4.0	3.9	3.8	2.2	1.9	2.0	1.9
	Yangatoke #	12.8	39.6	*	32.5	33.5	33.8	*	31.1	31.2	31.1

* Well not in existence; - gap in data collection; # well deepened after initial data collection.

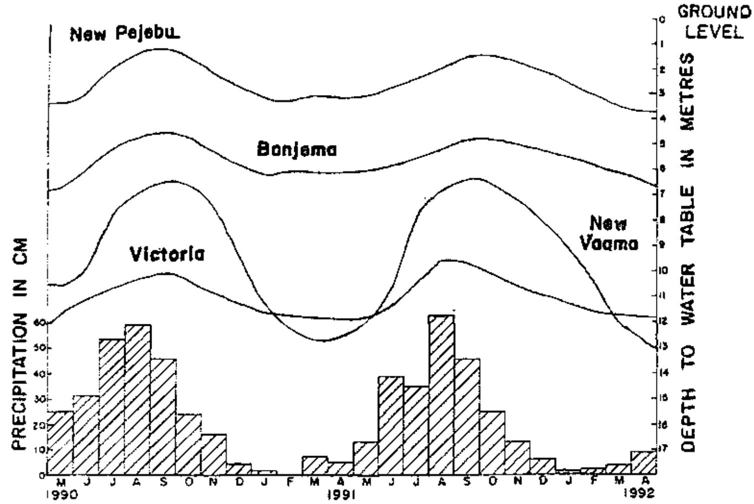

Fig. 3 Natural seasonal fluctuation of water table in response to precipitation.

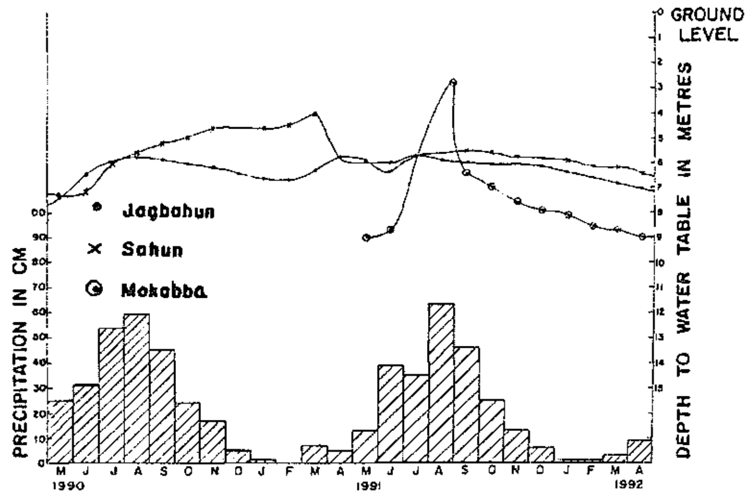

Fig. 4 Hydrographs of wells affected by damming.

height of the rainy season. A gradual decline begins as rainfall decreases with little or no recharge to the aquifer.

Draining of the Pejebu ponds following the move to Lanti lowered water levels in these two wells. Drops of 6.4 and 1.2 m between April 1991 and April 1994 have occurred at New Pejebu and New Vaama respectively.

Sahun is sited immediately downstream of dam B6 on Bamba-Belebu pond, mined out in 1989. In July 1990, the level of Bamba pond was raised from 41 m to 43 m to create a fish pond as part of mine rehabilitation activities. The increased hydraulic gradient between pond and aquifer, caused a continual anomalous rise in well water levels through peak dry season (February–April) as shown in Fig. 4. Waterlogging was visible in a downstream swamp in February 1990 that according to local reports normally shows receding levels at this time of year. An isolated depth to water table measurement of 7.3 m in January 1990 (Akiwumi *et al.*, 1990), compared to 4.7 and 6.3 m in January 1991 and 1992 respectively, further indicates a change in storage. Annual fluctuation in the following water year (May 1991–April 1992) was minimal due to reduced recharge.

Jagbahun well, downstream of the series of dams numbered P3–P8, also shows little fluctuation, since the Tikote has been drastically reduced by the many dams containing water in the Pejebu ponds. Draining of these ponds in April 1992, dropped the well level further, by 2.5 m as measured between April 1991 and April 1994.

Mokabba well level rose significantly following completion of dam C3 on a tributary of the Lanti in June 1991. In February 1992, dam L3 was completed further downstream of dam C3, creating central Lanti pond with a water elevation of 31 m. Elevation in Mokabba well at the time was also at 31 m. In March, the pond elevations in the part of the canal behind dam C3 and in central Lanti pond were dropped by 8 and 21 m respectively to facilitate the dredge move. The drastic change in hydraulic gradient has created a persistent groundwater mound around Mokabba.

Local transient flow systems

The hydraulic interrelationship between surface water and groundwater under both artificially induced and natural conditions is illustrated in Fig. 5. Figure 5(a) is a plot of monthly water elevations for Pejebu South pond and the wells at Bonjema and New Pejebu in the adjacent aquifer. At times of no spill in ponds, good correlation exists between hydrographs. In the wet season, when reservoirs attain maximum capacity and spill occurs, surface water levels are maintained while well levels continue to rise. The ponds, therefore, have become permanent discharge zones. The exception to this, under present conditions, is the relationship between Bamba fish pond and Sahun well. The April well elevation of 41.1 m measured in 1994 compared to 38.3 m in April 1991, after the pond level was raised, would suggest that the surface water level and water table are approaching a state of equilibrium.

The natural transient flow in areas not influenced by damming can be seen in the correlation between hydrographs of Nyandehun well sited 500 m from the Lanti and river stage prior to the completion of dam L2/L3 in February 1992. In the wet season the hydraulic gradient was from river to well and in the dry season the situation was reversed as shown in Fig. 5(b). The slight effect of damming on the riverflow regime is also illustrated in this figure. A pump test on this well further confirmed that the river acts as a recharge boundary.

In spite of the completion of dam L2/L3, no reduction in recharge to Nyandehun well has been measured. This is attributed to significant seepage beneath the dam, measured as increased discharge in the Lanti channel downstream in April 1992. Lamin *et al.* (1991) found the value to be five times greater than the value measured in April 1991. This is probably related to the underlying geology which comprises highly permeable, unconsolidated variegated sands that extend from the coast to 300 m upstream of Nyandehun.

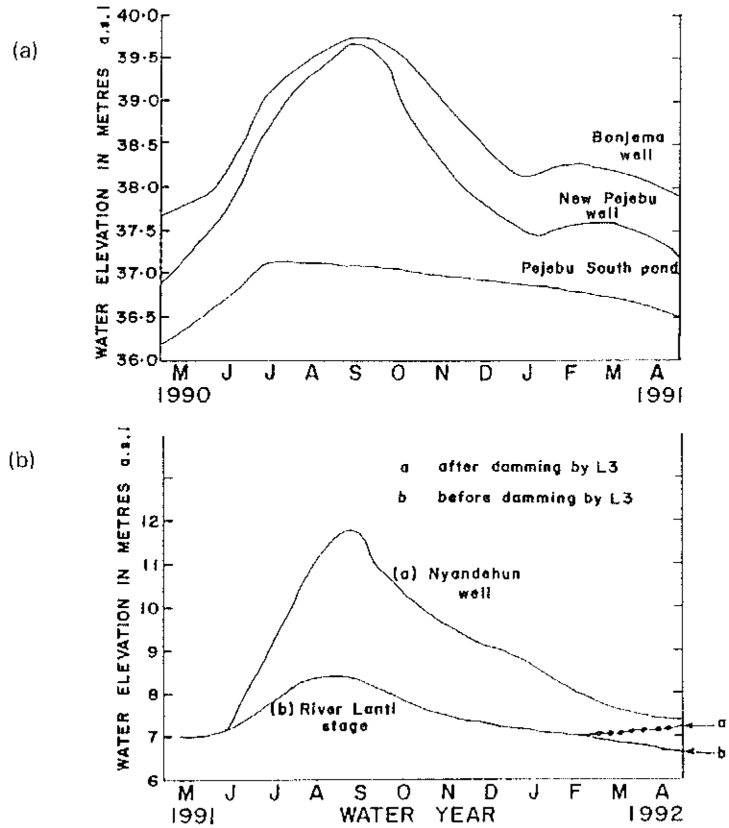

Fig. 5 Relationship between water elevation in ponds and aquifers: (a) Pejebu South pond and Bonjema and New Pejebu wells; and (b) River Lanti stage and Nyandehun well.

Regional flow directions

In spite of the presence of hill ranges, a dominant, natural southwesterly regional groundwater flow direction can be defined. Field studies by McKenzie (1963) revealed that drainage divides rarely follow the crestlines of high ground but have receded or been imprinted on lower ground, on the inland side of strike ridges. The divide of the Kokpoi with the Tikote and the Jong along the flank of the Gbangbama ridge line, for example, stands at 37 m and River Yambei rises in flat ground. Further, weathering is extensive and deep even on steep slopes of the Gbangbama and Imperi hills.

The series of dams on the Tikote River system are maintaining an elevated hydraulic head in the middle reaches of the basin. This has reversed the easterly flow of the river. As Fig. 6 shows, flow was largely converging on an area analogous to the main Tikote channel in April 1991. By April 1992, the additional dams and bunds associated with the canal route had modified this trend by redirecting groundwater flow southwards, towards the Kokpoi and Lanti basins.

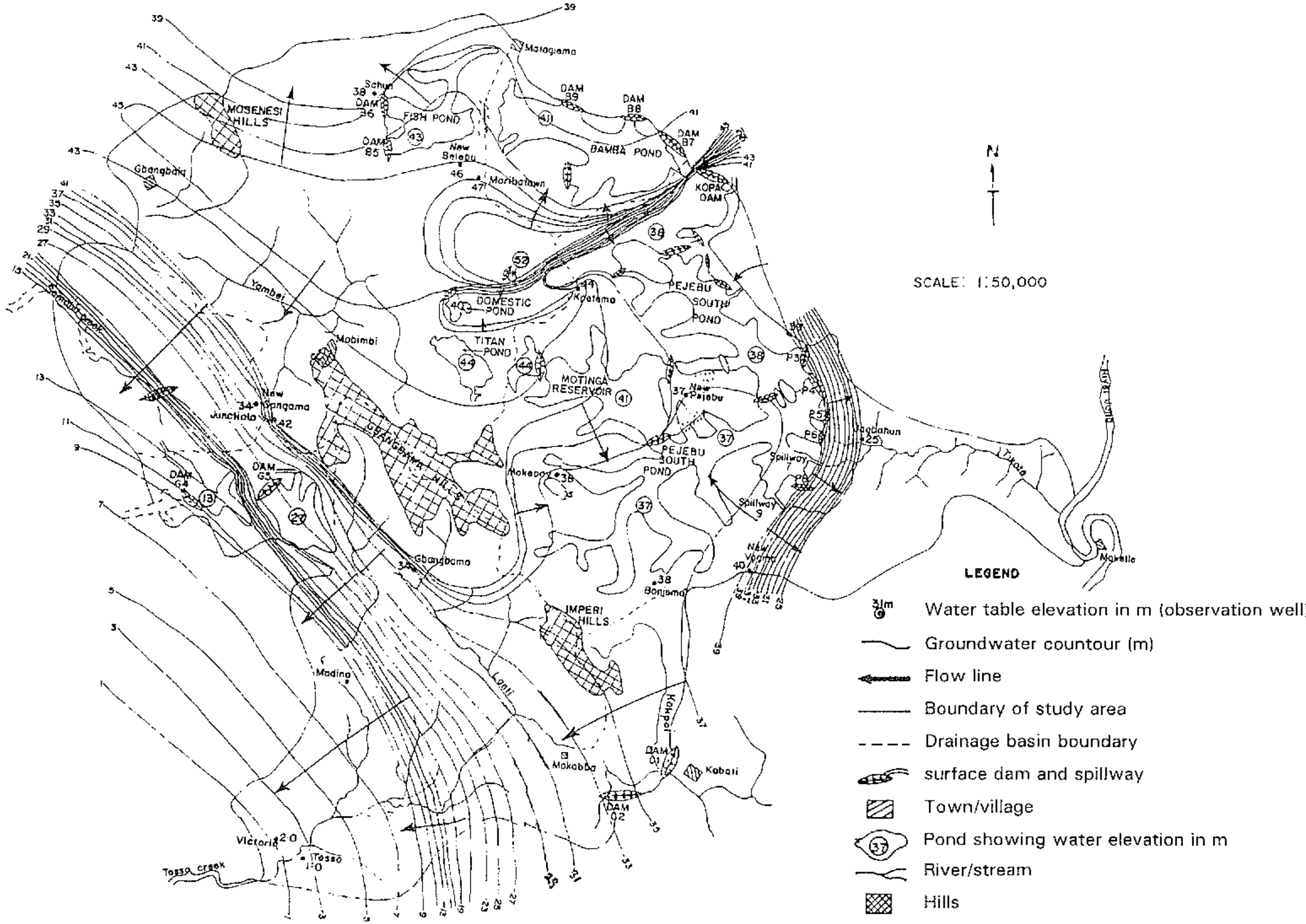

Fig. 6 Groundwater contour map of study area for water year 1990–1991.

CONCLUSION

In spite of the fair to low transmissivity of an extensive, shallow unconsolidated aquifer over fractured crystalline rock, groundwater levels in wells respond rapidly to artificially induced flow caused by raised water levels in surface channels.

Draining of Pejebu pond starting in mid 1992 to release water to Lanti canal, likewise caused a drop in water levels in Pejebu, New Vaama, Bonjema and Jagbahun wells. This trend has continued with gradual draining of the canal route through 1993 and 1994.

A reduction in recharge to some wells has occurred, notably Jagbahun due to its location immediately downstream of several dams. However, high seepage beneath dam L2/L3, as a result of the underlying geology, has prevented this from taking place in Nyandehun well.

Hydraulic interconnection between surface water bodies and the aquifer was verified by plots of river/pond stage and well water levels and pump tests on selected wells. Due to control of dredge pond levels by spillways on dams, the hydraulic gradient between surface water and aquifer generally remains in the direction of ponds throughout the water year.

Reversals in groundwater flow direction have occurred in the moderate to low relief basins of the Tikote and Kokpoi that have been most severely affected by damming.

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