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SUBMARINE GROUNDWATER DISCHARGE (SGD) PATTERNS THROUGH A FRACTURED ROCK: A CASE STUDY IN THE UBATUBA COASTAL AREA, BRAZIL

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Abstract: The flow of groundwater out across the sea floor has the potential to influence sedimentary processes, sea floor morphology, pore water chemistry and benthic habitats. Relatively few observations of the process of submarine groundwater discharge (SGD) have been made. Measurements along the South American coast and over fractured rock aquifers are especially rare. The rate and distribution of SGD was measured using vented, benthic chambers on the floor of Flamengo Bay located at the southeast coast of Brazil. Discharge rates were found exceeding 200 $cm^3 s^{-1}$ of pore water per cm^2 of sea floor per day (200 cm day^{-1}). Large variations in SGD rates were seen over distances of a few meters. We attribute the variation to the geomorphologic features of the fracture rock aquifer underlying a thin blanket of coastal sediments. Clustering of fractures and the topography of the rock-sediment interface might be focusing or dispersing the discharge of groundwater.

INTRODUCTION

As we will discuss, submarine groundwater discharge has sedimentological implications. Although the occurrence of submarine, freshwater springs have been recognized in the folk wisdom of millennia, the scientific inquiry into submarine groundwater discharge is a recent development. Study sites have been overwhelmingly in the northern hemisphere and usually either on unconsolidated or semi-consolidated coastal aquifers or in karst terrain (Taniguchi et al., 2002). Fractured rock aquifers present a special challenge because groundwater flows are confined to unseen fractures buried under a thin, and seemingly homogeneous, layer of coastal sediments. Few such sites have been investigated in detail, although some studies are available to indicate that submarine groundwater discharge (SGD) is significant in such situations. Examples are to be found on the Kamchatka Peninsula (Boldovski, 1996) where submarine groundwater discharge is estimated to occur at a rate of about 4.2 liters per second per kilometer of shoreline; on a volcanic island in the Korean Sea (Kim et al., 2003) where flow rates between 14 and 82 cm day^{-1} were measured; and on Hawaii (Garrison et al., 2003) where flow rates of 8.4 cm day^{-1} were found within about 1 km and 2.3 cm day^{-1} further offshore. We report in this article direct measurements of submarine groundwater discharge performed on the southeastern coast of Brazil.

As early as 1939, Douglas Johnson suggested that SGD might leave its mark on seabed morphology. He proposed SGD as a mechanism for the formation of submarine canyons off the east coast of North America. Although large submarine canyons have other causes, the dissolution of submarine limestone by SGD has been shown to create distinctive escarpments and box canyons at the continental margins (Paull et al., 1950). Other geomorphic features have also been recognized on a smaller scale. In the southeast Baltic Sea, pockmarks in fine-grained sediments have been identified as bathymetric expression of groundwater seeps (Khandriche and Werner, 1995; Wever and Fiedler, 1995; and Sauter et al., 2001). In Australia, rapid SGD through buried paleochannels create pits, locally referred to as *wonky holes* as far as 10 km from shore (Stielitz and Ridd, 2002).

The upward floor of pore water can influence sediment transport by reducing the current shear stress at the sea floor (Conley and Inman, 1994). Even at low rates of SGD the advective flux of pore water, and dissolved constituents, overwhelms diffusive transport and evidence suggest that gravitational instabilities caused by the flow of fresher groundwater into saline, open water substantially enhances irrigation of the sediments and mixing within the pore water (Bokuniewicz et al., 2004).

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SGD can also control the extent and distribution of biogenic influences on dynamics of the sediment-water interface. For example, nutrients supplied by SGD have been implicated in the appearance of macroalgal (e.g. *Ulva*) mats (Lapointe and O'Connell, 1989). The freshening of pore water by fresh SGD can produce microhabitats. For example, patches of *Marenzelleria viridis,* a polychaete tubeworm, mark low salinity seeps in the floor of Delaware Bay (Miller and Ullman, 2004). As an invasive species, submarine seeps may provide this brackish water worm «stepping stones» to span more saline, estuarine environments.

STUDY AREA

Flamengo Bay is in the Ubatuba region of the Sao Paulo State coast in southeastern Brazil (Fig. 1). The embayment is a semi-enclosed marine environment formed between the projections of the crystalline rocks of the Complexo Costeiro unit, where the Serra Mar mountains reach the shore. This unit is composed by Pre-Cambrian high-grade metamorphic rocks, granitic bodies with basaltic intrusions. The rocky shoreline is blanketed offshore with a layer of fine sand (4 to 5 ϕ; Mahiques et al., 1998). Despite the small drainage basins between the mountain range and the shore, freshwater discharge is sufficient to reduce the salinity of coastal waters (Ferreira et al., 1995).

A reconnaissance of submarine groundwater discharge using radon-222 as a natural tracer disclosed a substantial inflow of groundwater, which includes both fresh and saline pore water (Oliveira et al. 2003). Fluxes of groundwater in Flamengo Bay was calculated to average 4.3 cm^3 of pore water per cm^2 of the sea floor per day (or, in short, 4.3 cm day^{-1}). Direct measurements of submarine groundwater discharge were also made (Oliveira et al., 2003) using vented benthic chambers (Lee, 1977). Measured fluxes were approximately 21 cm day^{-1}. The disparity between these estimates may be explained by the spatial variability of SGD documented in this study. Areas of rapid seepage must be balanced by areas of low discharge in order to result in the integrated discharge measured by geochemical tracers. The measurements reported here were at the Lamberto beach in front of the base Clarimundo de Jesus of the Instituto Oceanografico de Universidade de Sao Paulo, Ubatuba, Brazil.

METHODS

There are three basic approaches to measure submarine groundwater discharge across the sea floor. Traditional measurements of hydraulic heads and permeability may be used in models to calculate the discharge. Alternatively a water budget may be calculated to include that volume of submarine groundwater discharge required to balance the budget. A second method uses geochemical tracers. Radium and radon are enriched in pore water and inventory of excess radium and radon in coastal waters can be interpreted in terms of the flux of groundwater across the sea floor (Oliveira et al., 2003).

Figure 1. Study site on the Brazilian coast. The IOUSP base at which the measurements were taken is in the northwest of Flamengo Bay as indicated.

Figura 1. Area de estudio en la costa de Brasil. La base de IOUSP donde se realizaron las mediciones está en el noroeste de la bahía Flamengo.

A third method, and the one used here, employs vented, benthic chambers embedded in the sediment to directly measure the SGD (Lee, 1977). These devices have been the subject of criticism due to potential artifacts introduced by the presence of the chambers themselves (e.g. Shinn et al., 2002). However, they have been widely used and experience suggests that they are reliable under calm conditions when the flow rate exceeds a few cm per day. The devices deployed in this study were provided by Dr Oliveira (Devisao de Radiometria Ambiental, Centro de Metrologia das Radiacoes, Instituto de Pesquisas Energeticas e Nucleares, Brazil). These measurements were part of a much more extensive experiment orchestrated by Dr Oliveira to intercompare various techniques for the measurement of SGD. The complete description of this experiment is beyond the scope of this paper.

Individual chambers covered an area of 2550 cm^3 (being the top of a standard 55-gallon drum). After emplacement of the sea floor, plastic bags were connected to the chambers and allowed to fill for time intervals between several minutes to over 2 hours. The bags were pre-filled will 1000 ml of ambient sea water

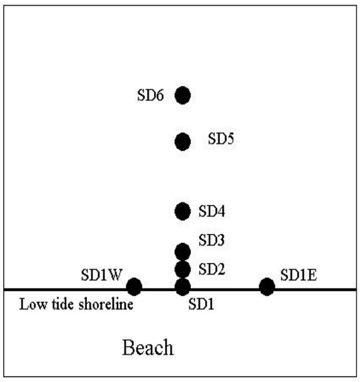

Figure 2. Approximate arrangement of seepage devices (SD). Actual spacing is given in the text.

Figura 2. Arreglo aproximado de los instrumentos percoladores (SD). El espaciamiento real se indican en el texto.

(e.g. Shaw and Prepas, 1989), except on occasions when it was desired to measure the salinity or other geochemical parameters of the SGD (these cases are indicated in Tables 1 and 2, Appendix). In those cases, after the chambers had been left in place long enough to flush the headspace, empty collection bags were used and the salinity of the discharged water could be measured with a refractometer. The measured flow rates were not obviously affected. Although it has been recommended also to leave the devices in place for twenty-four hours in order to achieve equilibrium before collecting samples, measurements at this site were

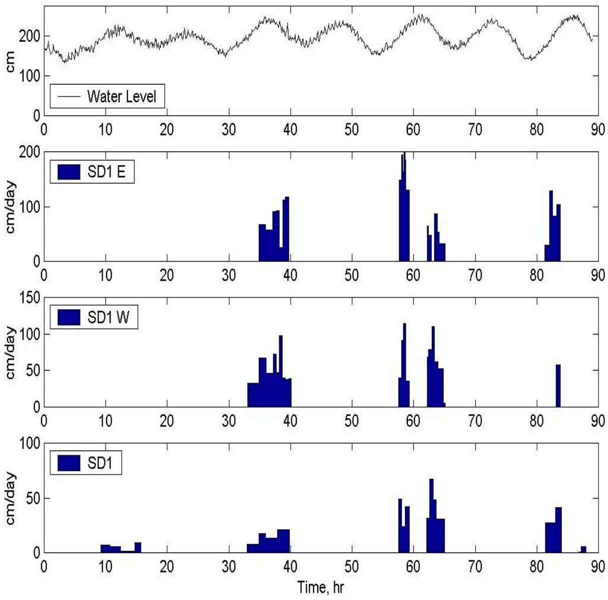

Figure 3. SGD measured at the low-tide shoreline. Time is in hours starting at midnight on 17 November 2003. Note the difference in the scale of the vertical axes.

Figura 3. SGD medido en la costa en marea baja. El tiempo es en horas desde la medianoche del at 17 Noviembre 2003. Note la diferencia en la escala de los ejes verticales.

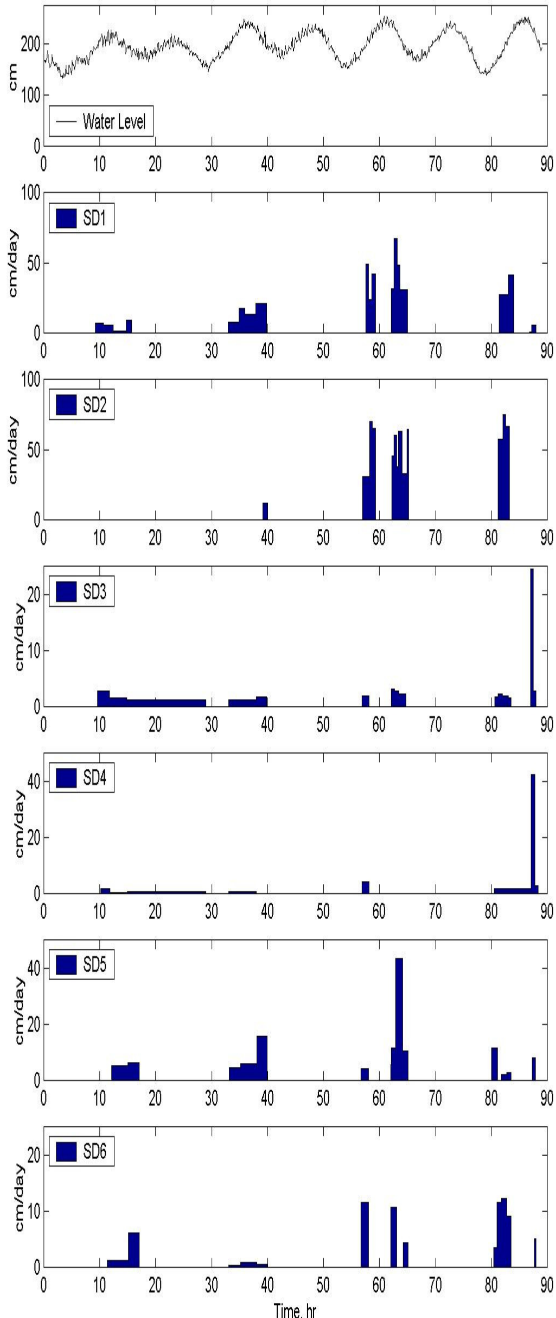

Figure 4. SGD measured along a transect offshore. Time is in hours starting at midnight on 17 November 2003. Note the differences in scale of the vertical axes.

Figura 4. SGD medido a lo largo de un perfil costa afuera. El tiempo es en horas desde la medianoche del 17 Noviembre 2003. Note la diferencia en la escala de los ejes verticales.

begun immediately because of the short duration of the field effort. The devices were left undisturbed in place, however, for as much as 90 hours.

Six devices were deployed along a transect perpendicular from shore (Fig. 2). The shoreward device (SD1) was exposed at low tide. The other five devices

(SD2, SD3, SD4, SD5 and SD6 were placed at distances of 5, 10, 18, 32 and 44 m from the low-tide shoreline. The respective water depths (LW) were 0 m, 0.33 m, 0.71 m, 1.07 m, 1.46 m and 1.65 m. The tops of the devices were between 0.05 and 0.15 m above the sea floor. Two more devices were placed approximately at the low tide shoreline east and west of the transect; one was placed 19 m alongshore to the east (SD1E) and one 14 m alongshore to the west (SD1W).

RESULTS

The measured seepage rates are shown in Figures 3 and 4. The highest rates of SGD were found at the low tide shoreline (SD1, SD1E and SD1W, Fig. 3, Table 1 Appendix) but they were not uniform. The device to the east (SD1E) recorded flow rates as high as 268 cm day^{-1} and collection bags with a capacity of about 6 liters had to be replaced every 10 minutes whereas at other locations flow rates were often sufficiently low that collections every hour or two are adequate. Along the cross-shore transect, relatively high rates were recorded at SD1 and SD2 and again at SD5 and SD6 (Fig. 4, Table 2 Appendix). The discharge was variable in time, but showed little relationship to the tidal stage. At other locations SGD has been found to be inversely related to the tide (e.g. Lee, 1977); discharge rates are lowest near the time of high tide.

It is interesting to note the high frequency oscillations on the tidal signal around for example, hour number 60. They have amplitude of about 0.15 m and a period of 10 to 20 min.These were noticed in the field at low tide when the shorewardmost devices were alternately exposed and submerged. These are likely to be seiches, the first recorded in Enseada do Flamengo. The bay is 6 to 7 m deep exceeding 12 m at its mouth. With a bay length (L) of 3 km, if an average water depth (h) of 10 m is assumed, the seiche period (T) would be 10 min for the first mode ($T = 2 L g^{-1/2} h^{-1/2}$).

The discharge seemed to increase over the course of the three-day experiment, however, the temporal changes were somewhat puzzling. At the beach on 17 November 2003, about 1 cm of rain fell during the first twelve hours and about 1.5 cm fell over the rest of the day. Light rain then continued for a half-day more but the weather was subsequently dry. The very high relief near the shore (up to 1,000 m) tends to trap moisture along the coast. It is possible that localized heavy rains had occurred also in the coastal range influencing the SGD. SD5 exceeded 5 cm day^{-1} and then 10 cm day^{-1} early in the experiment then to about 45 cm day^{-1}. Near the end of the experiment the discharge at SD5 and at SD6 seemed to be decreasing while that at SD3 and SD4 briefly increased. If the local rainfall were the cause of increased SGD, a time lag of about 40 hours would be required between the recharge and the SGD response at the sea floor.

Salinity was measured with a refractometer after the devices had been in place overnight. The lowest salinity recorded on the collected fluid was 20 at SD1E (the device recording the most rapid discharge rate). The flow rate here was sufficient to exchange the pore water to a depth of up to five meters along a flow line every day. The relatively high salinity indicates that mixing and recirculation of sediment pore water must be effective over flow paths at least several meters long. Even though the measured flow rates were adequate to flush the head space of other devices (such as SD1, SD5, and SD6), the measured salinities in the collected discharge remained indistinguishable from that of the ambient, open water. Salt water must be mixed and recirculated with any freshwater SGD.

DISCUSSION

Since the earliest use of vented benthic chambers, large variability in the results have been noted (McBride and Pfannkuch, 1975; Zietlin, 1980). In many locations, however, the SGD has been shown to be modulated by the tide despite large, unexplained variations. SGD is expected to be lower in high tide and more rapid at low tide (e.g. Lee, 1977). This has not been observed at all locations, however, including this one in Flamengo Bay; where tidal signal apparently was not a strong enough.

In principle, the SGD should decrease rapidly over a homogeneous aquifer with distance from the shore over the first 100 meters or so. This has been described as *exponential* although the mathematical function is not strictly true either in theory or as described by measured SGD. However, in many locations, this has proven to be useful description. At Ubatube there was a marked departure from this generalization, however. Along the transect, the highest rates were measured at the two locations closest to shore (SD1 and SD2) but the next two devices (SD3 and SD4) recorded little or no flow and relatively high flow was found at distance of 30 or 40 m from the low-tide shoreline. The most rapid flows, however, were off the transect; the longshore variation in flow rate being many times greater than the cross-shore trends. The fact that rates in excess of 200 cm day^{-1} were found with only eight, more-or-less random, placements of the devices suggests that areas of high seepage are common. Although spatial variations in SGD could be due to spatial heterogeneity in the permeability of the unconsolidated sediments, this would not explain temporal changes.

We postulate that the irregular distribution and high rates of SGD seen at Ubatuba is a characteristic of fractured rock aquifers. The bay floor sediments were sandy and not noticeably different from place to place in the study area. However, bedrock is exposed at the shoreline and an irregular rock surface was encountered at shallow depths offshore. Other investigators could drive probes to a depth of a few meters in some places but less than half a meter at other adjacent locations.

The water feeding the SGD is supplied to the bottom of the thin blanket of unconsolidated sediment through fracture system and concentrated (or dispersed) along the irregular surface of the buried rock. Presumably, this is fresh groundwater working its way seaward through the fractured rock. The relatively high salinity in the pore water of the sediment blanket, despite high discharge rates, must be due to some efficient mixing process in the surficial sediments themselves, perhaps a combination of gravitational, free convection and wave pumping (Bokuniewicz et al., 2004).

Our conceptual model of this system must allow for: a) the lack of an inverse relation between SGD with distance from shore as seen at other sites; b) large heterogeneity with very high and very low SGD being found within meters of each other, and c) a temporal variability that might allow areas of high discharge to shift laterally over short periods (days) apparently uncorrelated to rainfall or tides. We envision a fractured rock aquifer in which zones of high (and low) discharge are controlled, in part, by the clustering of fracture patterns and, in part, by the topography of the buried rock surface, which might focus or disperse groundwater flow through the unconsolidated cover depending on the thickness of cover and degree of lateral constriction. In a connected, but complex, fracture system, we can image how the zone of high SGD may shift from place to place over a period of days as the hydraulic heads in one part of the network of fractures are decreased by draining or increased by local recharge, perhaps out of sight in the coastal range. Rapid, but local, variation would propagate with unpredictable results through the interconnected system. This might be analogous to a complex, electrical grid where a change in voltage or resistance in one branch affects all other branches, in varying degrees.

CONCLUSIONS

In fractured rock aquifers, the SGD across a fairly homogeneous but then sediment blanket should be expected to be heterogeneous. Rates are likely to be controlled by the presence, or absence, of buried fracture systems and focused, or dispersed, by the topography of the buried rock surface. In such a situation, integrated SGD might best be described statistically from many, randomly situated, spot measurements. A better approach for regional, or even local, water budgets, may be the use of geochemical tracers in the open water that integrate over the range of SGD variation from place to place.

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APPENDIX

The seepage rates are provided in two tables. Table 1 shows the data from the three seepage devices at the low-tide shoreline (SD1, SD1E and SD1W). Table 2 shows the data from the cross-shore transect seaward of SD1, that is, SD2, SD3, SD4, SD5, and SD6. Time is given in hours starting at midnight on 17 November, 2003. For each seepage device, the seepage rate, in cm day^{-1}, is given between the times immediately above and below the entry. An asterisk indicates samples from collection bags that were not prefilled. If the salinity of the sample was measured, it is given, in ppt, next to the seepage rate in parentheses. Bay salinity was about 31.

SD1W		SD1		SD1E	
Time (hs)	cm /day	Time (hs)	cm /day	Time (hs)	cm /day
0	-	0	-	0	-
-	-	9,17	-	-	-
-	-	-	6,8	-	-
-	-	10,66	-	-	-
-	-	-	5,5	-	-
-	-	12,42	-	-	-
-	-	-	1,5	-	-
-	-	14,72	-	-	-
-	-	-	8,9	-	-
-	-	15,9	-	-	-
33,0	-	32,95	-	-	-
-	32,2	-	7,8	-	-
34,92	-	34,87	-	34,92	-
-	67,6	-	17,8	-	67,6
36,0	-	35,92	-	35,92	-
-	46,4	-	13,2	-	57,3
37,20	-	-	21,1*	-	91,0*
-	71,9*	-	21,1*	-	91,1*(24ppt)
37,65	-	-	-	-	-
-	46,7*	-	-	-	37,68
38,13	-	-	-	-	92,4*
-	97,9*	-	-	38,13	-
38,67	-	-	-	-	25,0*
	39,5*	-	-	38,72	-
39,17	-	-	-	-	112,5
-	37,6*	-	-	39,17	-
39,70	-	39,83	-	-	117,4*
-	38,5*	-	-	39,70	-
40,07	-	-	-	-	-
57,57	-	57,57	-	57,60	-
-	39,9*(30ppt)	-	49,1*(25ppt)	-	148,2*(20ppt)
58,03	-	58,0	-	58,0	-
-	91,0*(30ppt)	-	24,8*(32ppt)	-	19,0*(30ppt)
58,33	-	-	-	58,25	-
-	114,2*(30ppt)	-	-	-	164,2*(20ppt)
58,67	-	58,58	-	58,40	-
36,0*(27ppt)	-	-	41,7*(32ppt)	-	267,7*(30ppt)
-	-	-	-	58,58	-
-	-	-	-	-	185,1*(20ppt)
-	-	-	-	58,75	-
-	-	-	-	-	129,8*(20ppt)
59,25	-	59,25	-	59,27	-
-	57,8	-	31,2	-	64,5
64,42	-	62,62	-	62,43	-
-	79,1	-	67,0	-	47,1
62,98	-	-	-	62,92	-
-	109,8	-	-	-	-
63,33	-	63,15	-	63,32	-
-	61,8	-	48,1	-	87,3
63,93	-	63,63	-	63,87	-
-	52,3	-	31,1	-	53,1
64,80	-	64,97	-	64,12	-
-	5,7	-	-	-	31,6
65,13	-	-	-	65,13	-
-	-81,33	-	-	81,25	-
-	-	-	27,2*(32ppt)	-	29,8*
83,08	-	82,99	-	82,03	-
57,2*(28ppt)	-	41,5*(33ppt)	-	-	128,7*(23ppt)
-	-	-	-	82,58	-
-	-	-	-	-	82,4*(23ppt)
-	-	-	-	83,25	-
-	-	-	-	-	103,5*(23ppt)
83,83	-	83,98	-	83,83	-
-	-	86,82	-	-	-
-	-	-	1,0	-	-
-	-	87,18	-	-	-
-	-	-	5,5	-	-
-	-	87,92	-	-	-

Table 1. Indicates that the collection bag was not prefilled
Tabla 1. Indica que la bolsa no ha sido previamente llenada

SGD2 Time, hr	cm/d	SD3 Time, hr	cm/d	SD4 Time, hr	cm/d	SD5 Time, hr	cm/d	SD 6 Time, hr	cm/d
0		0		0		0		0	
	–	9.60	–	10.15	–		–		–
	_		2.8		1.9		_		_
		11.75		11.85		12.08		11.32	
	_		1.5		0.5		5.1		1.3
		14.78		14.95		15.03		15.13	
	_		1.2		0.7		6.3		6.1
			28.95		29.00		17.07		17.07
	_		0		0		_		_
		33.05		33.08		33.13		33.02	
	_		1.3		0.7		4.6		0.3
		35.05		35.08		35.15		35.20	
	_		1.3		0.6		6.0		0.9
39.10		37.93		38.00		38.08		38.10	
	11.9		1.8		_		15.7		0.5
40.05		39.83				39.92		39.95	
	–		–		–		–		-
56.92		56.88		56.88		56.70		56.70	
	31.1*		1.9*		4.1*		4.2*		11.6*
58.25		58.13		58.10		58.05		58.03	
	70.1*		0		0		0		0
58.67		62.13				62.05		62.00	
	65.2*(30ppt)		3.1		_		11.5		10.7
59.72		62.68				62.87		63.02	
	0		2.8		_		43.4		<0
62.18									
	45.7		–		–		–		–
62.57		63.43		63.55		64.17		64.27	
	60.2		2.3		0.1		10.5		4.4
63.02									
	37.8		_		_		_		_
63.40		64.67							
	62.8		_		_		_		_
64.02									
	32.6		_		_		_		_
64.87									
	64.0		_		_		_		_
65.18				65.10		65.07		65.08	
	–		–		–		–		–
		80.57		80.53		80.05		80.40	
	–		1.7		1.8		11.6		3.5
		81.17				81.03		81.00	
			2.3				<0		11.5
81.20	–								
	57.4		_		_		_		_
82.02		81.98						81.77	
	74.7*		1.9		_		_		12.2
82.58									
	66.3*(32ppt)		_		_		_		_
83.25									
						81.78			
							2.0		_
		83.03				82.78		82.78	
			1.5		_		2.8		9.1
		83.55		87.13		83.52		83.50	
			0		42.3		0		0
		86.97		87.77		87.33		87.67	
			24.4		2.7		7.9		5.1
		87.50				87.83		88.00	
			2.8		_				
87.97	88.33								

Table 2. Indicates that the collection bag was not pre-filled
Tabla 2. Indica que la bolsa no ha sido previamente llenada